XXXV. *An Experimental Inquiry into the Strength of Wrought-Iron Plates and their Riveted Joints as applied to Ship-building and Vessels exposed to severe strains.*

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Communicated by the Rev. Henry Moseley, *F.R.S.*

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The experiments herein recorded were instituted early in the spring of 1838, and before the close of the following winter most of them had been completed; owing however to a long series of professional engagements they have stood over (with the exception of some additions made in the following year) to the present time. The object of the inquiry was twofold—first, to ascertain by direct experiment the strength of wrought-iron plates and their riveted joints in their application as materials for ship-building; and secondly, to determine their relative value when used as a substitute for wood. On these two points it cannot be expected that our knowledge should be far advanced, as a very few years have elapsed since it was asserted that iron, from its high specific gravity, was not calculated for such a purpose, and that the greatest risk was likely to be incurred in attempting to construct vessels of what was then considered a doubtful material. Time has however proved the fallacy of these views, and I hope, in the following experiments, to show that the iron ship, when properly constructed, is not only more buoyant, but safer, and more durable than vessels built of the strongest English oak.

At the commencement of the experiments I felt desirous of conducting them upon a scale of such magnitude as would supply sound practical data, and at the same time establish a series of results calculated to ensure confidence as well as economy in the use of the material. My views were ably carried out by Mr. Hodgkinson, who conducted the experiments under my direction, and from whom I received valuable assistance.

In conducting the investigation I found it necessary to divide the subject into four distinct parts:—

1st. The strength of plates when torn asunder by a direct tensile strain in the direction of the fibre, and when torn asunder across it.

2ndly. On the strength of the joints of plates when united by rivets as compared with the plates themselves.

3rdly. On the resistance of plates to the force of compression, whether applied by a dead weight or by impact.

And lastly. On the strength and value of wrought-iron frames and ribs as applied to ships and other vessels*.

PART I.

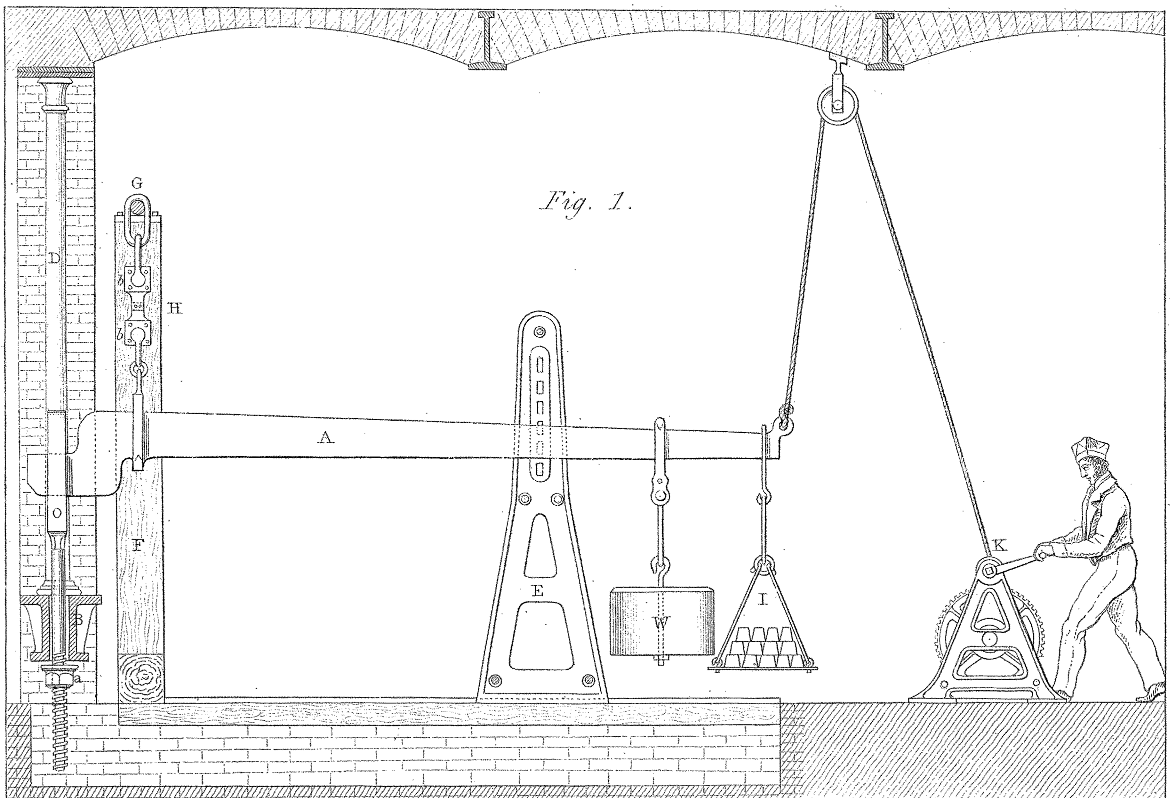
At the commencement of iron ship-building, in which I took an active part, the absence of acknowledged facts relative to the strength and varied conditions under which the material was applied, was the principal reason which induced me to enter upon this inquiry. I have extended the investigation into the best methods of riveting, and the proportional strength of rivets, joints, &c., as compared with the plates and the uses for which they are intended. The latter is a practical and highly important inquiry, as great difference of opinion exists amongst engineers and others, as to the form, strength and proportions of rivets, and the joints of which they form an essential part. I therefore considered an experimental investigation much wanted, not only on account of its important practical bearing, but what was probably of equal value, in order to remove existing discrepancies and to establish a sounder principle of construction founded upon the unerring basis of experiment. From these considerations I bestowed increased attention upon the inquiry, and endeavoured to render it practically useful. Before detailing the experiments, it may be necessary to describe the apparatus by which the results were obtained.

The annexed drawings, Plate LIV., represent a side and end view of the apparatus used in the experiments. The large lever A was made of malleable iron and was fixed to the lower cross beam B (fig. 1) by a strong bolt O, which passed through it at B. At the top end of this bolt a preparation was made to receive the end of the lever, and by means of the screw-nut at *a*, the lever A was raised or lowered to suit the length of the plates to be experimented upon. Upon the top side of the beam, and under the gable wall of a building five stories high, were placed two cast-iron columns, D, D, which retained the beam B in its place and prevented it from rising when the lever was heavily loaded during the experiment. The frame E guided the end of the lever and the weight W, and close to the fulcrum were placed two wooden standards,

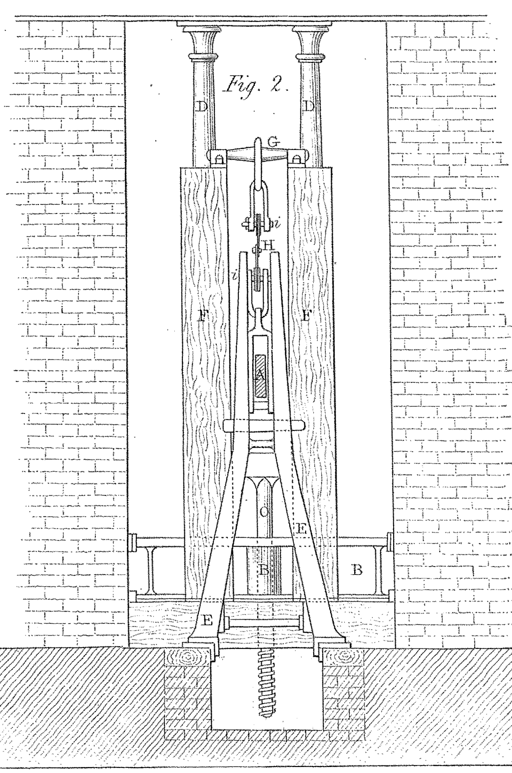
* Several important facts and improvements in the construction of iron ships have been ascertained since my experiments were made, but I apprehend none of them have tended in the least degree to diminish their value. Nor have they, to the best of my knowledge, been superseded by others of a more elaborate or more decisive character. It is true, that a series of interesting and important experiments have been made at the instance of the Admiralty on the effect of shot upon the sides of iron ships. At some of these experiments I had the honour to be present, and witnessed some curious and unexpected results.

The first series was conducted at the Arsenal, Woolwich, and subsequently others were made at Portsmouth. Both were important as respects the effect of shot upon wrought-iron plates, with enlarged and diminished charges of powder and at different velocities, but discouraging as regards the use of iron in the construction of ships of war. These experiments, however interesting in themselves, do not appear to be conclusive; and it is to be hoped that the apparent danger, indicated by the experiments, may yet be overcome, and the superiority as well as the greater security of the iron ship fully established.

Side View.



End View.



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F F, on which were fixed the cast-iron saddles receiving the cross bar G, from which the plates to be experimented upon were suspended. These plates were nearly all of the same form as shown at H, and were made narrower in the middle to ensure fracture in that part; the ends, as at *b*, *b*, had plates riveted to them on both sides, in order to strengthen them at those parts when attached to the bolts and shackle under strain.

The specimens thus prepared were suspended by the cross bolts *i*, *i*, and resting upon the standards were torn asunder by weights suspended from the large beam, as exhibited in the Plate.

In addition to the large weight W, a strong scale was attached to the extreme end of the lever at I, for the purpose of increasing the weights when required in the larger description of experiments, and by the application of a pair of blocks and the windlass K, the load was removed, and the changes produced upon the plates were by these means carefully determined.

The following data respecting the weight W, lever, shackle, &c., are taken from the actual weights from which the calculations are made:—

		lbs.
W.	The weight with its carriage	2552
A.	The weight of the beam	1070
2 A.	The weight of the beam	2140
3 A.	The weight of the beam	3210
K.	Shackle	24
4 K.	Shackle	96
6 K.	Shackle	144

Experiments to ascertain the Strength of Plates, &c.

In the following experiments all the plates were of uniform thickness, and of the form exhibited in fig. 2 in the column of remarks; the ends had plates riveted to them on both sides to render them inflexible; they had holes, 0, 0, bored through them perpendicular to the plate, in order to connect it by bolts, with the apparatus for tearing it asunder in the part A B, which was made narrower than the rest. The centres of the holes 0, 0 were in a direct line through the middle between A and B*.

Table I. Strength of Plates.—Low Moor Yorkshire Iron.

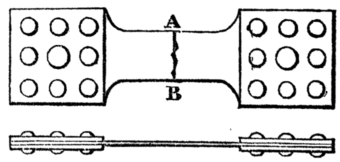
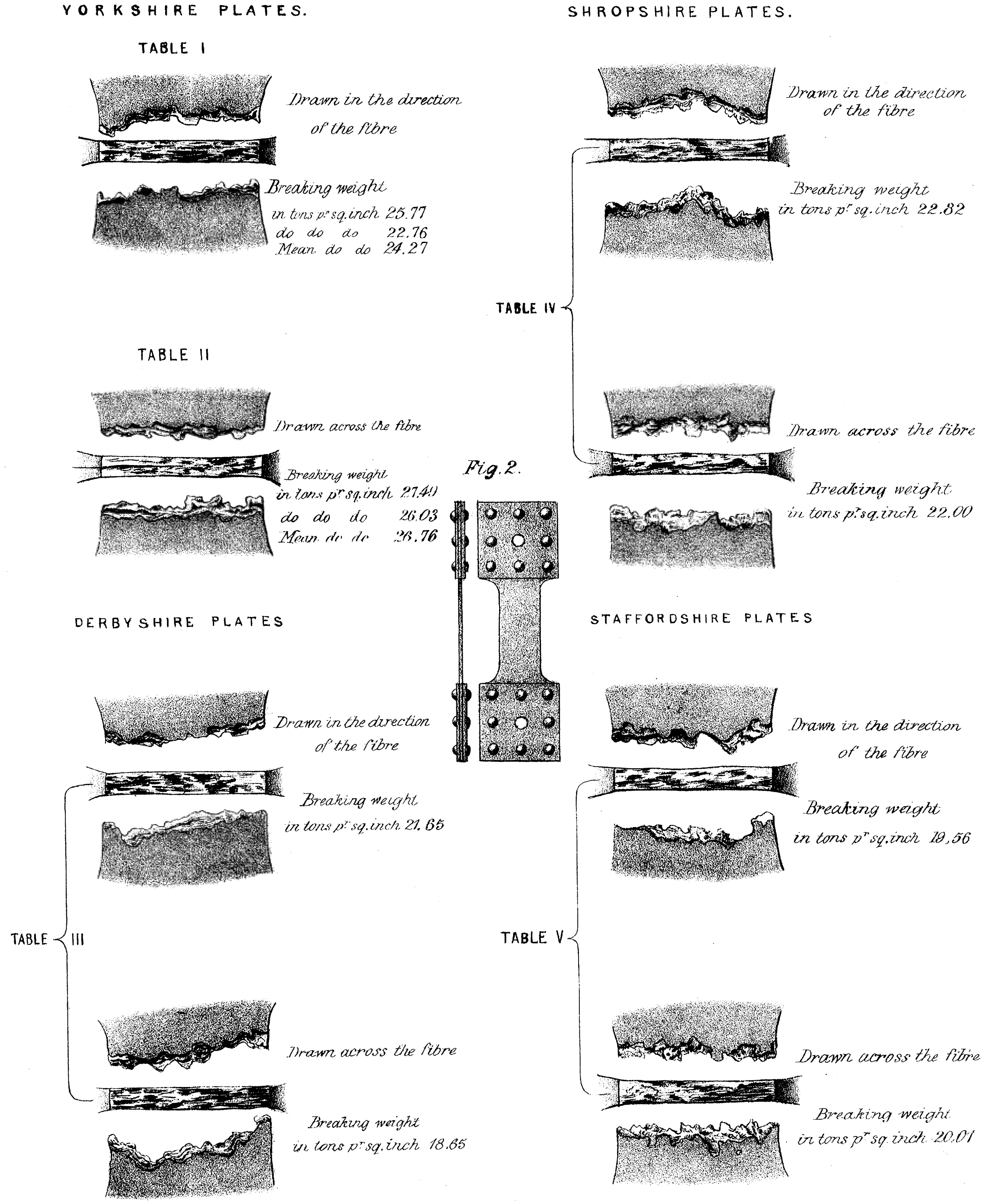
No. of exp.	Description of plate and dimensions in the middle.	Weight laid on in lbs.	Reduced dimensions in middle of plate through weights laid on.	Breaking weight in lbs.	Mean breaking weight in lbs.	Remarks.
	Drawn in the direction of the fibre.					Fig. 2. Plan and section of the plates, the line AB being that of the fracture.
1.	Area of section in middle 2·00×·22=·44 in.	24,043	1·96×·21			
		25,531	1·89×·19	25,531		
2.	....	23,571	Reduced.			
		24,747	1·93×·18	24,747	25,400, or 25·77 tons per square inch.	
3.	....	25,923	1·94×·18	25,923		All the plates were laminated as if formed of three or more plates, the external ones being thinner than the internal ones†. In the last experiment there was a disunion between the lamina which admitted the point of a penknife.
4.	Same iron drawn across the fibre. Area of section 2·00×·22=·44 in.	23,179	Altered.			
		24,355	1·99×·215			
		25,923	....			
		27,099	2·2×·19	27,099	27,099, or 27·49 tons per square inch.	This, it will be seen, did not break at the narrowest place.

Table II. Strength of Plates.—Low Moor Yorkshire Iron.

No. of exp.	Description of plate and dimensions in the middle.	Weight laid on in lbs.	Reduced dimensions in middle of plate through weights laid on.	Breaking weight in lbs.	Mean breaking weight in lbs.	Remarks.
5.	Same iron as in Table I., drawn across the fibre. Area of section 2·00×·22=·44 in.	24,355	Stretching.			The form and size of specimen as before, fig. 2. In these experiments it was observed, as in No. 4. in the preceding Table, that the plate did not break at the narrowest part, a circumstance the more anomalous, as there did not appear to be anything in the apparatus to cause it.
		26,315	21·5 ×·20	26,315		
6.	....	23,571	2·25×·20	23,571	25,662, or 26·037 tons per square inch.	
7.	Same iron, thicker plates, drawn in direction of fibre. Area of section 2·00×·26=·52 in.	27,099	Thickness ·25	27,099	....	Very uniform in texture.
	....	25,923	1·96×·24	25,923	26,511, or 22·76 tons per square inch.	The fracture of this specimen showed a great want of regularity; about one-third of the area had the appearance of steel. All the other plates appeared to be uniform, but laminated, as mentioned before.

* For the appearance of the fractures see Plate LV.

† Nearly the whole of the plates manufactured in this country are laminated, owing to the manner in which the shingles are formed, by piling a number of flat bars one upon another, which are made larger or smaller according as the plate may be required heavier or lighter.



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The results obtained from the Low Moor plates in the preceding Tables give fair indications of their strength. It will be observed, on comparing the mean of the breaking weights in this case with the experiments of Brown and Telford, that there is a very slight difference between the strength of plates and bar iron.

Taking the results of Captain Brown, we have in eight experiments on Swedish, Welsh and Russian iron, 25 tons as a mean of the breaking weight when reduced to an inch square.

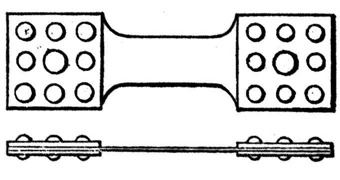
In Mr. Telford's experiments on Swedish, Welsh, Staffordshire and faggoted iron, the mean breaking weight obtained from nine different bars was $29\frac{1}{4}$ tons to the square inch. The comparison will then be—

Captain Brown's experiments, 25 tons to the square inch	Mean 26·41 tons.
Minord and Desames' experiments, 25 tons to the square inch . .	
Mr. Telford's experiments, $29\frac{1}{4}$ tons to the square inch	

Yorkshire plates' experiments, $24\frac{1}{2}$ tons to the square inch.

Making the strength of plates to that of bars as 24·5 : 26·4, being a comparatively small difference in their respective powers to resist a tensile force.

Table III. Strength of Plates.—Derbyshire Iron.

No. of exp.	Description of plate and dimensions in the middle.	Weight laid on in lbs.	Reduced dimensions in middle of plate through weights laid on.	Breaking weight in lbs.	Mean breaking weight in lbs.	Remarks.
9.	Drawn in the direction of the fibre. Area of section 2·00×·28in. (Mean 2·00×2·85=·57)	21,219 28,667	Stretched. 2·00×·27	28,667		Form of specimen the same as shown in Table I. fig. 2. 
10.	2·00×·29in.	21,219 22,789 26,707	Sinking. Sinking. 2·15×·27	26,707	27,687, or 21·68 tons per square inch.	There was a stripe resembling steel across the fracture near one side.
11.	Plates drawn across the fibre. Area of section 2·00×·28=·56 in.	22,395 23,179	Stretching. Thickness ·27	23,179	....	In the broken surface there seemed to be a stratum of steel, the rest was laminated but imperfectly.
12.	2·00×·28=·56 in.	24,747	2·00×·28	24,747	23,963, or 18·65 tons per square inch.	Short streaks of steel in fractured surface.

If we compare the results in the Derbyshire plates with those in the preceding Tables, we have in the mean of four experiments a ratio of 20·165 : 24·850, or 5 to 6 nearly.

Again, by comparing the same plates with the mean strength of bars reduced to an inch square, the difference will be as 20 to 26, being an excess of 6 tons in favour of the bars.

TABLE IV. Strength of Plates.—Shropshire Iron.

No. of exp.	Description of plate and dimensions in the middle.	Weight laid on in lbs.	Reduced dimensions in middle of plate through weights laid on.	Breaking weight in lbs.	Mean breaking weight in lbs.	Remarks.
13.	Drawn in the direction of the fibre. Area of section 2·00×·265=·53 in.	......	....	28,275		Form of specimen the same as showu in Table I. fig. 2. In the first experiment the fracture showed an iron very uniform, except a few bright spots like steel.
14.	....	......	....	25,923	27,099, or 22·826 tons per square inch.	Experiment 2. Appearance of fracture as before, but a crack up the middle showed that the plate was formed of two plates of equal thickness, not well united.
15.	Plates of the same iron drawn across the fibre. 2·00×·265=·53 in.	......	....	26,315	26,119, or 22 tons per square inch.	Fracture as before, with a laminated diversion, as in last experiment.
16.	....	......	....	25,923		

The Shropshire iron gives better indications of strength than those obtained from the Derbyshire plates; the mean breaking weights in the last Table being 22·41 tons. From the Yorkshire plates we have a mean breaking weight of 24·85 tons, exhibiting a difference of $2\frac{1}{2}$ tons in favour of the Yorkshire iron, and 2 tons or about $\frac{1}{10}$th greater than the Derbyshire.

TABLE V. Strength of Plates.—Staffordshire Iron.

No. of exp.	Description of plate and dimensions in the middle.	Weight laid on in lbs.	Reduced dimensions in middle of plate through weights laid on.	Breaking weight in lbs.	Mean breaking weight in lbs.	Remarks.
17.	Drawn in the direction of the fibre. 2·00×·26=·52 in.	......	....	23,571	22,787, or 19·563 tons per square inch.	Form of specimen the same as before, fig. 2. Fracture dark grey colour, very similar to that from the four preceding plates.
18.	....	......	....	22,003		It had however a few specks of bright matter in it, and was without any laminated appearance.
19.	Plates of the same iron drawn across the fibre. Area of section 2·00×·265=·53 in.	......	....	24,335	24,943, or 21·01 tons per square inch.	Irregular in texture, air-bubbles in fractured surface, with bright crystallized matter like steel. This iron has much of the same irregularity as the Derbyshire iron.
20.	....	23,571	The thickness ·26	25,531		Surface of fracture showed the iron to be very irregular, one-half being bright matter like steel.

On comparing the strengths of the different irons, it appears that the Derbyshire and Staffordshire plates are nearly equal, the former indicating 20·165 tons as the mean of the breaking weight per square inch, and the latter, as in the preceding Table, 20·28 tons per square inch. The same comparison further applies to the above and those made on the Derbyshire plates in Table III.

Taking therefore the results as derived from these experiments, it will be observed, that in every instance little or no difference appears to exist in the resisting powers of plates, whether drawn in the direction of the fibre or across it. This fact is clearly established by the following comparison, which evidently shows, that in whatever direction the plates are torn asunder, their strength is nearly the same.

	Mean breaking weight in the direction of the fibre, in tons per square inch.	Mean breaking weight across the fibre, in tons per square inch.
Yorkshire plates...............	25·770	27·490
Yorkshire plates...............	22·760	26·037
Derbyshire plates	21·680	18·650
Shropshire plates	22·826	22·000
Staffordshire plates	19·563	21·010
Mean............	22·519	23·037

Or as 22·5 : 23·0, equal to about $\frac{1}{45}$ in favour of those torn across the fibre*.

From the above it is satisfactory to know, so far as regards uniformity in the strength of plates, that the liability to rupture is as great when drawn in one direction as in the other; and it is not improbable that the same property would be exhibited, and the same resistance maintained, if the plates were drawn in any particular direction obliquely across their fibrous or laminated structure.

In order however to establish the relative powers of resistance in plates of rolled iron, I have endeavoured to tabulate the results, as derived from the preceding experiments, in such form as will indicate their respective values, and place them in comparison with each other, and also with those made on bars by TELFORD and BROWN. The comparisons are made from the Yorkshire plates, as producing the best results; and conceiving them to be a fair average of the strength of rolled iron, I have selected them as the standard of comparison.

Comparative results of rolled iron as derived from experiment, the Yorkshire plates being unity.

Names of Iron.	No. of experiments.	Mean breaking weight in tons per square inch.	Mean breaking weight in tons per square inch.	Ratio of the strength of plates drawn in the direction of the fibre, and across it. Also of rolled and faggoted bars drawn in the direction of the fibre.
Yorkshire plates...............	8	25·514	....	
Derbyshire plates	4	....	20·160	1 : 0·7882
Shropshire plates	4	....	22·413	1 : 0·8789
Staffordshire plates	4	....	20·264	1 : 0·7946
Mean............	....	25·514	20·945	1 : 0·8209
From Mr. TELFORD and Captain BROWN's experiments on bars	....	....	26·41	1 : 1·0351

* In some experiments by NAVIER upon the strengths of plates of wrought iron, both in the direction of the fibre and perpendicular to it, he found them as 40·8 to 36·4. The new methods of piling the rough bars before rolling may however account for the difference, and in a great measure determines the strength of the plate. In this country the process of piling is by equal layers of flat bars at right angles to each other, which produces great uniformity of strength and texture in the manufacture. At other places there is sometimes a difference in the mode of piling, which varies the texture of the plate, and also the strength of the layers are greater in one direction than another.

Here it will be observed that the difference between the strength of the Low Moor plates in their resistance to a tensile strain, when compared with bar iron, is inconsiderable; but taking the mean of the other irons, viz. the Derbyshire, Shropshire and Staffordshire, there is a falling off in the strength of about 21 per cent., the ratio being in favour of bar iron as 1·035 : ·8209.

In treating of the strength of iron, it may be useful to compare the foregoing experiments on the tensile strength of plates with those of a similar description on timber. On this subject I feel the more desirous of establishing a comparison, as the two kinds of material are now applied to similar purposes, such as ship-building and other constructions, and the question becomes every day more important as to which of the two materials is the best. There is every reason to believe that the advocates of improvement would arrange themselves on the side of iron, and those for the "wooden walls" would be equally zealous on that of timber. This is however a question which time and experience alone can determine, and conceiving that our knowledge of the properties of iron, as a material for ship-building, is far from perfect, we may safely leave its final decision to the evidence of experimental research, and a more extended application of its practical results.

When we attempt a comparison of the value of one material, in its application to a specific purpose, with that of another material similarly applied, the comparison is only correct when the two materials are placed in juxtaposition, or when they are contrasted under the same circumstances as to the trials and tests to which they are respectively subjected. Now in this comparison I am fortunate in having before me the able experiments of Musschenbrock, Buffon, and those of a more recent date on direct cohesion by Professor Barlow of Woolwich. I have selected from the experiments of the latter those which appear to approach most nearly to the present inquiry; and impressed with the conviction of their having been carefully conducted and being from English timber, I attach the greatest value to them.

According to Musschenbrock's, the strengths of direct cohesion per square inch of the following kinds of timber are as follows:—

	lbs.		lbs.
Locust-tree	20,100	Pomegranate	9750
Locust-tree	18,500	Lemon	9250
Beech and oak	17,300	Tamarind	8750
Orange	15,500	Fir	8330
Alder	13,900	Walnut	8130
Elm	13,200	Pitch pine	7630
Mulberry	12,500	Quince	6750
Willow	12,500	Cyprus	6000
Ash	12,500	Poplar	5500
Plum	11,800	Cedar	4880
Elder	10,000		

From BARLOW the strengths are,—

	lbs.		lbs.
Box	20,000	Beech	11,500
Ash	17,000	Oak	10,000
Teak	15,000	Pear	9800
Fir	12,000	Mahogany	8000

Mr. BARLOW, in adverting to the experiments of MUSSCHENBROCK, observes, that some of them differ considerably from his own, a circumstance probably not difficult to account for, as the different degrees of dryness have a great effect upon the strength of timber*.

Dr. ROBISON, in speaking of the experiments of MUSSCHENBROCK, states, that we may presume they were carefully made and faithfully narrated, but they were made on such small specimens, that the unavoidable natural inequalities of growth or texture produced irregularities in the results which have too great a proportion to the whole quantities observed. It is for the same reason that I give preference to Mr. BARLOW's results, as he observes, "that the experiments from which they are drawn were made with every possible care the delicacy of the operation would admit." Assuming therefore that BARLOW is correct, and taking the mean strength of iron plates, as given in the preceding Tables, at 49,656 lbs. to the square inch, or calling it 50,000 lbs., and the resistance of the direct cohesion of different kinds of timber as given by Mr. BARLOW, the following ratio of strengths will be obtained:—

	Timber lbs.	:	Iron. lbs.	Ratio, taking timber as unity.
Ash	17,000	:	50,000,	or as 1 : 2·94
Teak	15,000	:	50,000,	or as 1 : 3·33
Fir	12,000	:	50,000,	or as 1 : 4·16
Beech	11,500	:	50,000,	or as 1 : 4·34
Oak	10,000	:	50,000,	or as 1 : 5·00

Hence it appears that the direct cohesion of iron plates is five times greater than oak; or in other words, their powers of resistance to a force applied to tear them asunder is as 5 to 1, making an iron plate $\frac{1}{2}$ inch thick equal to an oak plank of $2\frac{1}{2}$ inches thick. In the teak wood and fir specimens, which exhibit greater resisting powers, nearly the same rule will apply, and thinner planks, as regards the tensile strength, would answer the purpose. This is a circumstance which may be applicable to teak wood, but unfavourable to fir when viewed as a building material exposed to a great variety of strains, or when used for sheathing and similar purposes in the art of ship-building. The teak wood being timber of greater density and of

* It has been shown by Mr. HODGKINSON, that timber, when wet, will be crushed by a force less than one-half of what would take to crush it when dry. It therefore follows that much depends upon the samples selected and the way in which the timber has been seasoned.

higher specific gravity, is better calculated to resist shocks than a tough fibrous substance of a soft and spongy nature, such as fir.

On this subject it should however be noticed, that whatever material is used for covering the ribs of vessels, it should be strong and elastic, in order to resist not only the force of direct tension, but that of lateral and compressed action. In a ship at sea these forces are strikingly exemplified, and that under circumstances embarrassing as well to the practical builder as the man of science.

Remarks on the foregoing experiments.

Having determined the strength of iron plates when drawn in the direction of the fibre as well as across it, and having compared the results with experiments of a similar character on timber, it may be useful to offer a few general observations on the question now under consideration.

Dr. Robinson, in his article on the strength of materials*, when discussing the nature of a stretching force applied to materials, observes, "that in pulling a body asunder the force of cohesion is directly opposed with very little modification of its action; that all parts are equally stretched, and the strain in every transverse section is the same in every part of that section." From this it would appear, that a body of a homogeneous texture will have the cohesion of its parts equal, and since every part is equally stretched, it follows that the particles will be drawn to equal distances, and the forces thus exerted must be equal. Now if this were true, the application of an external force to a body might be increased to such an extent as not only to separate the parts furthest asunder, but ultimately to destroy the cohesion of all the particles *at once*, a circumstance under which instantaneous rupture would follow as a result. These views are however not borne out by facts, as the experiments of Mr. Hodgkinson on iron wire show that the same iron may be torn asunder many times in succession without impairing its strength†; and some recent experiments at the Royal Dockyard, Woolwich, clearly show, that an iron bar may be stretched until its transverse section is considerably reduced and ultimately broken without injury to its tensile strength. Nay, more, the same iron (so elongated), when again submitted to experiment, exhibited increased strength, and continued to increase, under certain limitations, beyond the bearing powers of the same bar in its original form‡. That all the parts of a body "subjected to a tensile strain are equally stretched" is therefore questionable. Bodies vary considerably in their powers of resistance, and exhibit peculiar properties of cohesion under the influence of forces calculated to tear them asunder. Fibrous substances, for instance, such as ropes and some kinds of timber having their fibres twisted, are enabled to resist tension under the influence of considerable elongation without impairing their ultimate strength.

* Encyclopædia Britannica.

† Manchester Memoirs, vol. v.

‡ I am indebted to Mr. Thomas Loyd of the Admiralty for a series of interesting results on this subject. See Appendix.

Many of the fibres are stretched, but only to the extent of bringing the others to bear upon the load, which done, their united force constitutes the maximum of resistance to a tensile strain.

Other bodies of less ductility and more of a crystalline structure, such as cast iron, stone, glass, &c., seem to be subject to the same law. In these cases it seldom happens that the whole of the particles are brought into action at once, as much depends upon the conditions of the body, the unequal state of tension of its parts, and the strain which some of the particles must sustain before the others receive their due portion of the load. Should the non-resisting particles be within the limits of elongation of the other particles, the body will then have attained its maximum power of resistance; but in the event of rupture to any of the resisting particles, the cohesive force of the body is thereby reduced, and that to the extent of the injury sustained by the fractured parts.

"There are however," as Dr. ROBINSON truly observes, "immense varieties in the structure and composition of bodies which lead to important facts, and prove that the absolute cohesion of all bodies, whatever be their texture, is proportional to the areas of their sections." Undoubtedly this is the case in bodies having an uniform texture with straight fibres, and hence it follows that the absolute strength of a body, resisting a tensile strain, will be as the area of its section.

The peculiar nature of the material combining a crystalline as well as a fibrous structure has led to these observations. In some instances the specimens experimented upon exhibited an almost distinct fibrous texture, and in others a clearly developed crystalline structure*. At other times some of the specimens were of a mixed kind, with the crystalline and fibrous forms united; the fracture having a laminated appearance, with the crystalline parts closely bound on each side by layers of the fibrous structure. These varieties are probably produced in the manufacture, and may be easily effected either by the mode of "piling" the layers of bars which form the plate, or from the unequal temperature of the parts as they pass through the rolls. But whichever way they are produced, it is evident, from the experiments, that the fractures gave, in most cases, indications of an unequal and varied texture.

In the foregoing experiments, and also in those which follow, great attention was paid to the appearance of the fracture, in order to ascertain the structure of the plate, and to determine how far it could be depended upon in its application to the varied purposes for which it was intended.

These appearances are all shown in the drawings appended to the experiments, and to which I beg to refer.

* See the fractured parts of the different specimens, Plate LV.

PART II.

On the Strength of Iron Plates united by Rivets, and the best mode of Riveting.

The extensive and almost innumerable uses to which iron is applied, constitute one of the most important features in the improvements of civilized life. It contributes to the domestic comforts and commercial greatness of the country, and from its cheapness, strength and power of being moulded, rolled and forged into almost every shape, it is not only the strongest, but in many respects the most eligible material for the construction of vessels exposed to severe strain. Large vessels composed of iron plates, such as steam-boilers, cisterns, ships, &c., cannot however be formed upon the anvil or the rolling-mill. They are constructed of many pieces, and these pieces have to be joined together in such a manner as to ensure the requisite strength and effect all the requirements of sound construction. This operation is called riveting, and although practically understood, it has not, to my knowledge, on any previous occasion, received that attention which the importance of the subject demands.

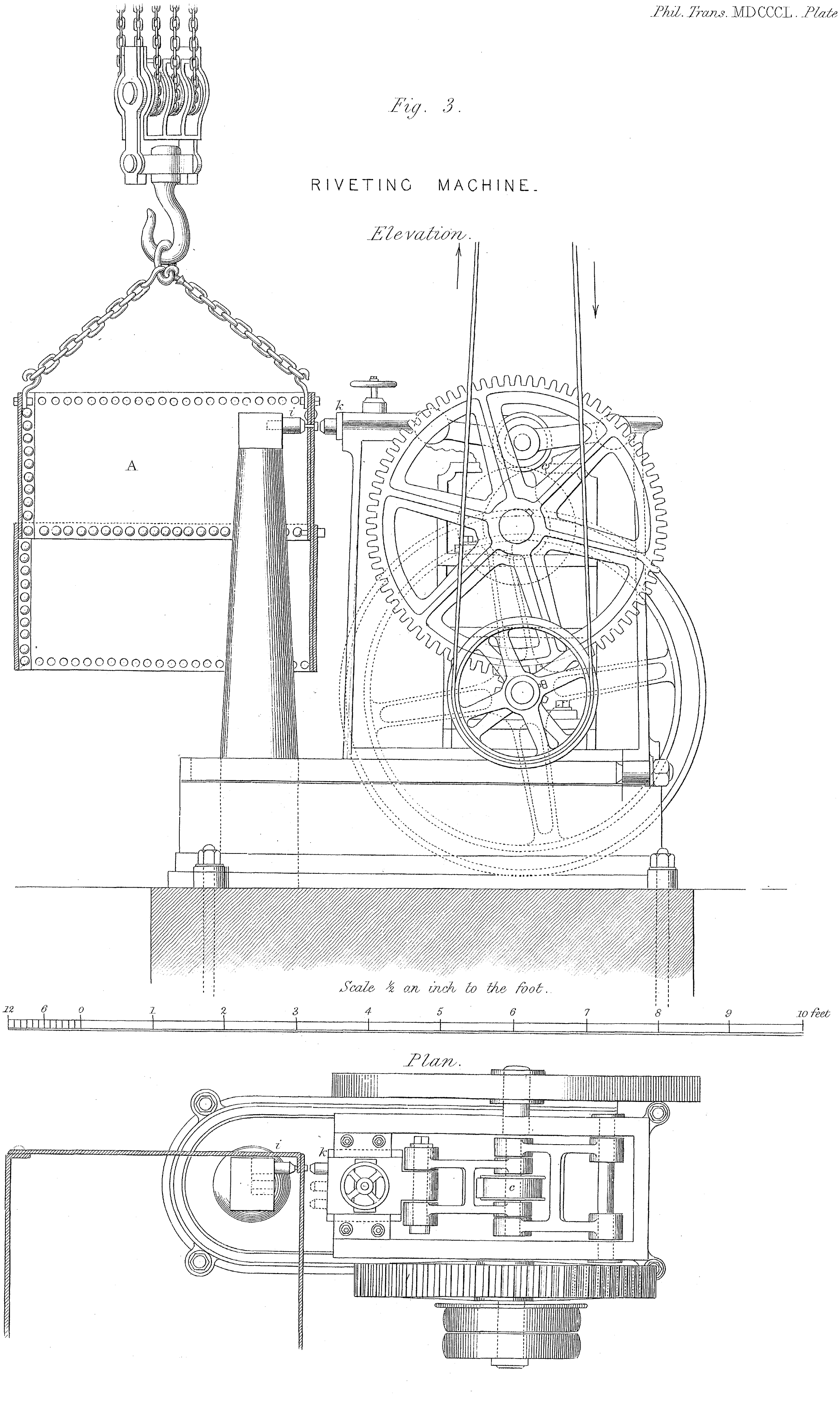
Up to the present time* nothing of consequence has been done to improve or enhance the value of this process. We possess no facts or experiments calculated to establish principles sufficient to guide our operations in effecting constructions of this kind, on which the lives of the public as well as the property of individuals depend. In fact, such has been our ignorance of the relative strength of plates and their riveted joints, that until the commencement of the present inquiry the subject was considered of scarcely sufficient importance to merit attention. Even now, it is by many assumed that a well-riveted joint is stronger than the plate itself, and a number of persons, judging from appearances alone, concur in that opinion. Now this is a great mistake, and although the double thickness of the joint indicates increased strength, it is nevertheless much weaker than the solid plate, a circumstance of some importance, as we hope to show in the following experiments.

It would probably be superfluous to offer any lengthened description of the principle upon which wrought-iron plates are united together; riveting is so familiar to every person in this country, that it might appear a work of supererogation to attempt it; and, assuming that the usual method of riveting by hammers to be generally known, we shall proceed to describe another method by machinery which effects the same object in considerably less time and at less cost, and completes the union of the plates with much greater perfection than could possibly be done by the hand. In hand-riveting it will be observed, that the tightness of the joint and the soundness of the work depends upon the skill and also upon the will of the workman, or those who undertake to form the joint and close the rivets. In the machine-riveting neither the will nor the hand of man has anything to do with it, the machine closes the joint and forms the rivet with an unerring precision, and in no instance can imperfect work be accomplished so long as the rivets are heated to the extent compressible by the machine.

* 1838, when these observations were written.

Fig. 3.

RIVETING MACHINE.



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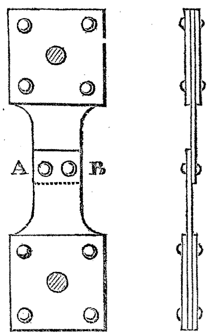
This property of unvarying soundness in the work, constitutes the superiority of the machine over the hand-riveting. The machine produces much sounder work, as the time occupied in the hand process allows the rivet to cool, and thus by destroying its ductility, the rivet is imperfectly closed, and hence follow the defects of leaky rivets and imperfect joints. It is evident that an instrument, such as the riveting-machine, having sufficient force to compress the rivet at once, or within an almost infinitely short period of time, must obviate, if not entirely remedy, these evils, as the force of compression being nearly instantaneous, the heads on both sides cannot be formed until the body of the rivet is squeezed tight into the hole; and in every case (even where the holes are not exactly straight) the compressed rivets are never loose, but fill the holes with the same degree of tightness as if placed directly opposite to each other. If, for example, we take a circular boiler, such as represented at A*, Plate LVI. fig. 3, and having all the perforations made and the plates attached to each other by temporary bolts and suspended over the machine in the position as shown at A, and having brought the holes in a line with the die marked *i*, *k*, the machine then is set to work, and by means of the cam or excentric raising the pulley of the elbow-joint C, the die *k* is advanced against the fixed die *i* in the wrought-iron stem, and the rivet is compressed into the required form with an increasing force as the die advances which gives the "nip," or greatest pressure, at the required time, namely, at the closing of the rivet.

From this description it will appear that a very limited portion of time is occupied in the process, and as twelve rivets can be inserted and finished by the machine in a minute, it follows, from the rapidity of the operation and the absence of hammering, that the ductility of the rivets is retained, and their subsequent contraction upon the plate renders the joint perfectly tight and the rivets sound in every respect. Under all the circumstances the machine-riveting is preferable to that executed by the hammer; it saves much time and labour, and that in proportion of 12 to 1, when compared to a long series of impacts applied by the hammer.

Having described the process of uniting wrought-iron plates by rivets, it may be of some importance to know the value of joints thus formed as regards their strength when compared with the plates themselves. To attain this object, and satisfactorily to determine their powers of resistance to a tensile strain, a great variety of joints were made, and having prepared the different specimens with the utmost care and attention, they were submitted to the test of experiment as follows:—

* The plan represents the machine in the act of riveting the corners of a square cistern or a locomotive fire-box.

TABLE VI. Strength of riveted Plates.—Yorkshire Iron*.

No. of exp.	Description of plates and mode of riveting.	Weight laid on in lbs.	Changes produced by weights.	Breaking weight in lbs.		Form of specimen and mode of fracture.	Remarks.
21.	Plates 22 inches thick, overlap joints, two rivets half-inch diameter, lap $1\frac{1}{2}$ inch, AB = 3 inches, riveted by the patent machine.	......	....	20,011	Mean 20,127	Fig. 4. 	Torn across at the rivet-holes.
22.	Same as last, area ·44 in.	......	....	18,667			Rivet-holes torn out.
23.	....	......	....	21,703			Rivet-holes torn out.
24.	Plates as before, riveted by the hammer, the rivets half-inch diameter, being of the usual length, but rather shorter than those used for the machine.	14,839	....	16,115	Mean 16,107	Specimen same as before, fig. 4.	Rivet-heads broke off and the plate torn across them in consequence.
25.	....	15,343	Plates bent.	16,099		....	Rivet-heads cracked across and rivet-holes torn out.
26.	Plates same as before and riveted by the hammer, with half-inch rivets, the rivets being a little longer and 2 inches lap	14,839	Plates bent nearly into a direct line with straining force.	17,833	Mean 18,982	Specimen same as before, fig. 4.	Here the rivets were the same length as the machine rivets, experiments 1, 2, 3, and were worked with great care on both sides. Both rivet-heads broken and the plate torn across them.
27.	....	14,839	....	20,131		....	Torn across at rivet-holes, and one rivet-head split.
28.	Plates same as before, lap 2 inches, and the rivets the same as in the last experiment, but riveted by the machine	14,839	Plates bent into a direct line by the straining force.	19,123	Mean 19,147	Specimen same as before, fig. 4.	Both rivets cracked across, metal torn across the rivet-holes.
29.	....	18,667	Joint apparently sound.	19,171		....	Torn across at the rivet-holes, both rivets slightly cracked near the head.

The plates used in the foregoing experiments are of Yorkshire iron, the same as those employed in Tables I. and II. The specimens were prepared in the same manner and of the same thickness, but 1 inch wider at the joint. This was done in order to retain sufficient metal round the rivet-holes, making the breadth of the plate the same after the rivet-holes were punched out as that of the plates torn asunder in the preceding experiments. In all these experiments only two half-inch rivets were used in the breadth of the plate. The lap was however increased, after the three first experiments, from $1\frac{1}{2}$ to 2 inches, to give greater strength in the longitudinal line of the plate and to prevent the metal tearing in that direction. This precaution was

* The nature and appearance of the fractures of all the irons and their riveted joints are shown in Plate LVII.

TABLE. VI.

Fig. 4.

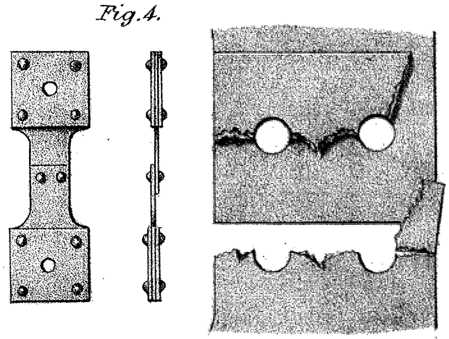


TABLE. VII.

Fig. 5. *Fig. 6.*

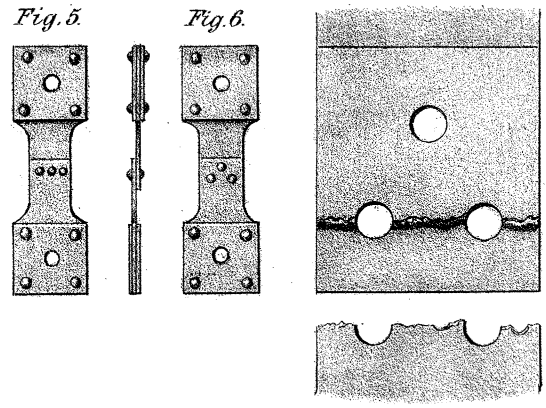


TABLE. VIII.

Fig. 7. *Fig. 8.*

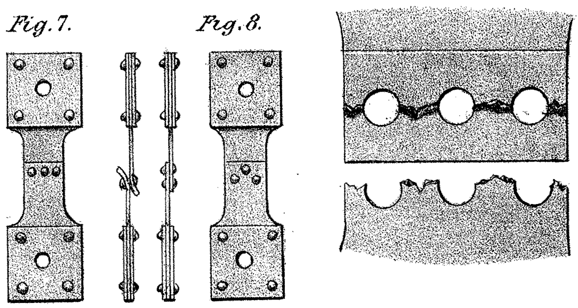


TABLE. IX.

Fig. 9.

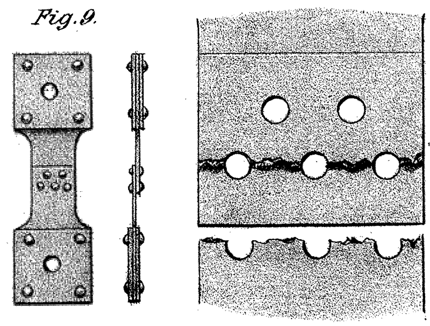
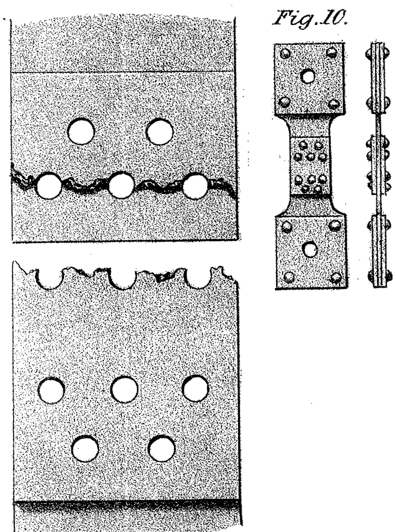


TABLE. X.

Fig. 10.



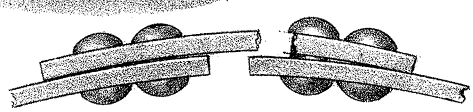


TABLE. XI.

Fig. 11.

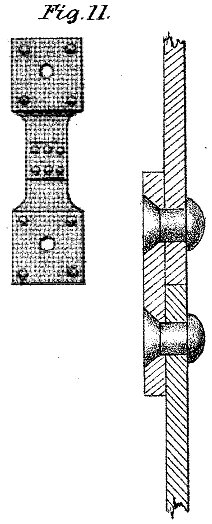


TABLE. XII.

Fig. 12.

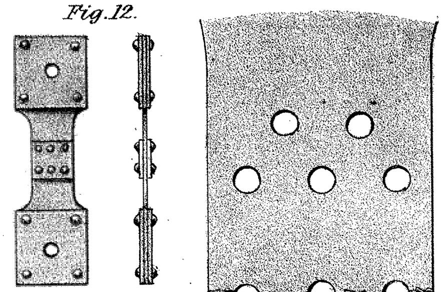
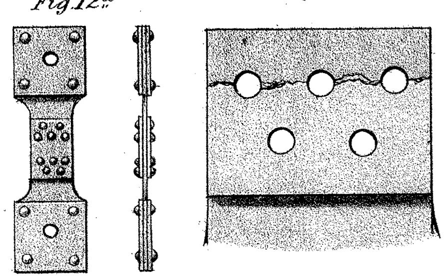


Fig. 12ª.



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found necessary, as the metal gave indications of weakness in consequence of the lap being rather narrow. Another reason for enlarging the lap was a desire at the commencement to begin with the least possible quantity, and by direct experiment to ascertain the maximum distance which the plates should overlap each other in the joints, and to determine the strongest and best form of uniting them. To these points every attention was given, for the purpose of collecting the facts on which are founded the tabulated results on that part of the subject which treats of the comparative dimensions of rivets and extent of the lap in reference to the thickness of the plates. In this department of the inquiry will be found the depth of lap, diameter and length of rivets, and the distances of holes for nearly every description of joint; also the thickness of the plate, with a column of strengths as deduced from the experiments.

If we examine the nature of the fracture in the foregoing experiments, it will be found that the machine-riveting is superior to that done by the hammer; the mean of the three first experiments being to the mean of the fourth and fifth as 5 : 4. In the eighth and ninth the strengths are nearly the same.

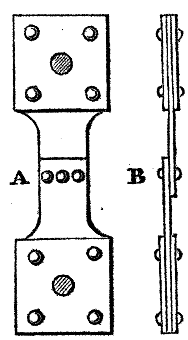
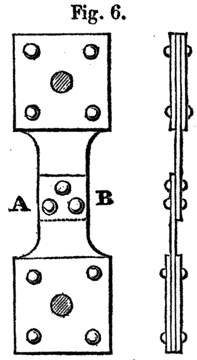
On comparing the strength of plates with their riveted joints, it will be necessary to examine the sectional areas taken in a line through the rivet-holes with the section of the plates themselves. It is perfectly obvious, that in perforating a line of holes along the edge of a plate, we must reduce its strength; and it is also clear, that the plate so perforated, will be to the plate itself nearly, as the areas of their respective sections, with a small deduction for the irregularities of the pressure of the rivets upon the plate; or in other words, the joint will be reduced in strength somewhat more than the ratio of its section, through that line, to the solid section of the plate. For example, suppose two plates, each 2 feet wide and three-eighths of an inch thick, to be riveted together with ten $\frac{3}{4}$-inch rivets. It is evident that out of 2 feet, the length of the joint, the strength of the plates is reduced by perforation to the extent of $7\frac{1}{2}$ inches; and here the strength of the plates will be to that of the joint as 9 : 6·187, which is nearly the same as the respective areas of the solid plate, and that through the rivet-holes, namely, as 24 : 16·5. From these facts it is evident that the rivets cannot add to the strength of the plates, their object being to keep the two surfaces of the lap in contact, and being headed on both sides, the plates are brought into very close union by the contraction or cooling of the rivets after they are closed. It may be said that the pressure or adhesion of the two surfaces of the plates would add to the strength; but this is not found to be the case, to any great extent, as in almost every instance the experiments indicate the resistance to be in the ratio of their sectional areas, or nearly so.

If we take the ultimate strength of the Yorkshire plates in Tables I. and II., it will be found that the mean breaking weight of eight specimens, each with a sectional area of ·46 inch, is 26,168, and the strength of the single joint*, of the same description of plates with an area of ·44 inch, is 18,591; this reduced gives the ratio of the

* I use the term single joint to distinguish it from the double riveted joint, which will be treated of hereafter.

strength as 25,030 : 18,591, or as 1 : ·742, the comparative strength of a single riveted plate of equal area through the line of the rivets. It will be observed that in this comparison the areas of the sections are nearly equal, and consequently there is a difference in strength between the solid part of the plate and that part where the perforations have been made of 32 per cent. The difference is considerable, but it probably arises from the narrowness of the specimen and the lateral strain induced by the position of the rivet, and the bending upwards of the end of the plates. From these facts I would infer that single riveting is weaker, and probably the loss of strength in this description of joint, including loss caused by the rivet-holes, is not less, under ordinary circumstances, than 40 per cent.

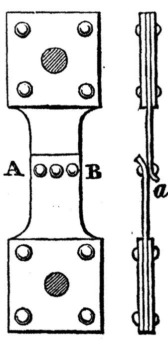
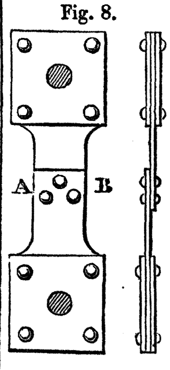
TABLE VII. Strength of riveted Plates.

No. of exp.	Description of plates and mode of riveting.	Weight laid on in lbs.	Changes produced by weight.	Breaking weight in lbs.	Form of specimen and mode of fracture.	Remarks.
30.	Plates 22 inches thick, with three rivets, eaeh $\frac{3}{8}$ inch diameter, AB 3 inchcs, lap $1\frac{1}{2}$ inch, area through rivet-holes ·4125......	14,839	Bent into a straight line.	16,603	Fig. 5. 	The plates were sound, but two of the rivets were cut directly across. Rivets too weak.
31.	Plates the same as before, overlap joints differing from the last in having three rivets $\frac{1}{2}$ inch diameter, forming an isosceles triangle, AB 3 inches ...	18,667	Joint apparently sound.	22,699 (Mean 23,035)	Fig. 6. 	With the first weight the plates became bent, so as to be in a direct line with the straining force.
		20,683	Single rivet slightly opened.			
		22,027	The other two rivets quite tight.			Tore across the two rivet-holes, in the direction AB.
32.	Same as before	18,667	Separation at end of plate, single rivet slightly opened.			With 22,027 lbs. the single rivet seemed somewhat opened, but the other two seemed quite close.
		22,027	....			Plate torn across at the single rivet and one of the double ones.
		23,035	Slightly drawn at the rivets............	23,371		Rivets sound in this and the preceding experiment.

In the first experiment the rivets (two in number) were evidently too weak, which caused them to shear directly across as if cut by a pair of scissors. In the next experiment the rivets were increased in number and size, which gave an excess of strength to the retaining power of the rivets and caused the plate to tear. If we take the mean of the experiments as respects the area of the rivets to that of the plates,

we find two half-inch rivets about the proportion, or the area of the rivets in the last experiments should have been ·4 inches, which is nearly equal to the area of the plate through the rivet-holes*.

Table VIII. Strength of riveted Plates.

No. of exp.	Description of plates and mode of riveting.	Weight laid on in lbs.	Changes produced by weight.	Breaking weight in lbs.	Form of specimen and mode of fracture.	Remarks.
33.	Plates same as before, ·22 inch thick, but wider, AB being 3½ inches, with three rivets ½ inch diameter, all in a line; lap 1¾ in.	18,667	Ends of plate much separated by bending.	19,675	Fig. 7. 	Though the ends of the plates were much separated, the light of a candle could not be seen through the line of the rivets. Plate torn across the rivet-holes.
34.	Thicker plates ·26 in. thick, in other respects the same as in experiments 31, 32, Table VII.; lap 3 inches; rivets ½ inch diameter	18,667 22,699	Ends of plate separated, joints apparently good. One plate much bent; joint apparently good.	23,707 } Mean 25,387	Fig. 8. 	Tore across the two rivet-holes.
35.	Plates the same as the last..................	21,019	One end separated so far as to exhibit the single rivet.	27,067 } Mean 25,387		Tore across the two rivet-holes, where the breadth was 3⅛ inches.

Here the section of the rivets is to that of the plates, through the line of the rivets, in the ratio of ·58 to ·44; had they been equal, it is probable that fracture would have taken place as soon by the rivets shearing as through the plates.

During the whole of the experiments on single riveted joints, it was observed that the ends of the plates under strain curled upwards on each side, and produced a diagonal strain upon the plates, which materially reduced the strength of the joint, as shown at *a* fig. 7.

This position gave an oblique direction to the forces, and caused the plate to break in some degree transversely through the rivet-holes. In order to obviate this defect, and prevent as much as possible a transverse strain upon the plates through the

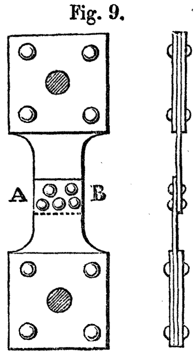
* Subsequent experiments made for ascertaining the strength of rivets (*vide* experiments on the strength of rivets for the Britannia and Conway Tubular Bridges) fully corroborate these views, namely, that riveted joints exposed to a tensile strain are directly, or nearly so, as their respective areas, or in other words, the collective areas of the rivets are equal to the sectional area of the plate taken through the line of the rivets.

points in contact, the lap was increased and a third rivet introduced to keep down the ends of the plates.

The sketches in the 31st experiment, Table VII., and those in the 34th and 35th experiment, Table VIII., represent the form of joint, and the methods adopted for securing the plates in the direct line of the strain.

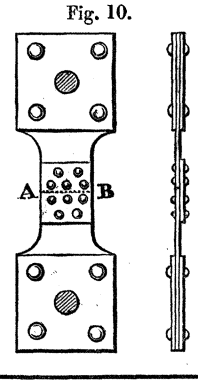
On comparing the breaking weights, it will be seen that the increased lap, with a rivet to keep down and retain the ends of the plates, gives a considerable accession of strength, and exhibits several important facts in connection with the construction of vessels exposed to severe pressure. But this becomes more apparent in the forthcoming experiments on the double-riveted joints.

TABLE IX. Strength of riveted Plates.

No. of exp.	Description of plates and mode of riveting.	Weight laid on in lbs.	Changes produced by weight.	Breaking weight in lbs.	Form of specimen and mode of fracture.	Remarks.
36.	Double-riveted plates ·22 inch thick; overlap joints riveted with five rivets of $\frac{3}{8}$ inch diameter each; lap 2 inches; AB=3 inches in breadth ...	16,115	Plates bent in a right line between the points of tension.		Fig. 9. 	Torn right across at the three rivet-holes, all the rivets being sound after fracture.
		21,715	Little or no alteration.	24,043		
37.	Plates the same as before, except that AB=$2\frac{7}{8}$ inches in breadth	18,667	Plates bent into right line, as before.	21,019 (Mean 22,531)		Broke as before; rivets all sound.

In these experiments, as in those in the preceding Table, the area of the rivets is in excess, and hence follows rupture through the plates.

TABLE X. Strength of riveted Plates, &c.

No. of exp.	Description of plates and mode of riveting.	Weight laid on in lbs.	Changes produced by weight.	Breaking weight in lbs.	Form of specimen and mode of fracture.	Remarks.
38.	"Jump Joints." Plates the same as before, both riveted to an extra plate of the same thickness laid on one side of them; lap of extra plate over each end 2 inches; each plate riveted by five rivets $\frac{3}{8}$ inch diameter; AB=$3\frac{1}{8}$ inches.	14,839	Bent into straight line.		Fig. 10. 	Tore across the rivet-holes.
		19,627	All sound.			Rivets sound after fracture.
		21,691	Rivets sound; plates much bent.	23,371		
39.	Same as above......	18,667	Bent nearly into a straight line.			
		22,699	Rivets sound; joint apparently good.	24,043 (Mean 23,707)		Tore across as before; one rivet-head crooked.

The same observations will apply to these experiments as to the last; the area of the rivets is in excess of that of the plates.

The system of double riveting exhibits several remarkable properties as regards strength, and the plates appear to retain their position under strain much better than single-riveted joints. These circumstances have induced a comparison of the results of the preceding experiments with those contained in Tables VII., VIII., IX. and X. The experiments in Tables VII. and VIII. give indications of increased strength by a slight enlargement of the lap and the introduction of a single rivet to keep down the end of the plate. In those experiments it was found that the additional rivet gave an increase of 26 per cent. over those obtained from the single rivets; a circumstance which suggested a further extension of the experiments, accompanied with a minute investigation of the parts, in order to ascertain their relative strengths, and the strongest form of joint.

The mean breaking weights of equal sections of single-riveted joints, as given in Table VI. and taken from nine experiments, are respectively as follows:—

$$\begin{array}{r}\text{lbs.}\\ \left.\begin{array}{r}20{,}127\\ 16{,}107\\ 18{,}982\\ 19{,}147\end{array}\right\}\end{array}\text{Mean . . } 18{,}590$$

giving a mean of 18,590 lbs. for the strength of single-riveted joints. Now in the second and third experiments, Table VII., with the rivets inserted in the shape of an isosceles triangle (which in fact is double riveting), and of equal sections to the specimens in Table VI., the mean breaking weight is 23,035, which gives an excess of 4445, or a ratio of 10 : 8 in favour of the experiments recorded in Table VII.

In the experiments (Table X.), the area of the section, taken through the line of the rivet-holes, is ·44 inch, or precisely equal to the section of the specimens experimented upon in Table VI., in which the mean breaking weight is 18,590 lbs. In these experiments the breaking weight is 23,707 lbs., which is rather more than that in Table IX., where the material had a smaller section, but having its dimensions exactly corresponding with the proportions given above. It therefore follows that in plates jointed with single rivets, the ratio of the strength of the single rivets is to that of the double-riveted joints as 8 to 10, the latter being one-fourth stronger.

It has been ascertained that it required a weight of 23,707 lbs. to tear asunder double-riveted plates, $3\frac{1}{8}$ inches wide and ·22 inches thick, with a flush joint, having a plate on the back and held together by five $\frac{3}{8}$-inch rivets on each side; the quantity of metal between the holes, in a direct line across the plate, being $\cdot 2 \times \cdot 22 = \cdot 44$ inch, which is the same transverse section as those operated upon in the first Table.

Now if we take the mean breaking weights of the riveted joints in Tables X. and VI. and compare them with the section of the plate itself as given in Table I., the areas being the same, we have for the tensile strength of plates—

	Section of iron torn asunder.	lbs.
In Table I., solid plate	·44	25,400
In Table X., double-riveted joints	·44	23,707
In Table VI., single-riveted joints	·44	18,590

Assuming therefore the strength of the plates to be 1000, we have—

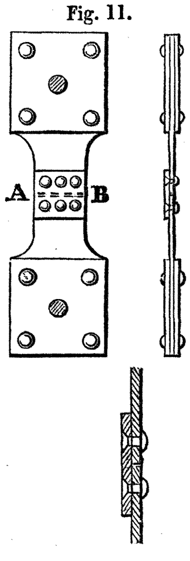
For the strength of plates of equal sections	1000
For the double-riveted joints	933
For the single-riveted joints	731

We may safely assume these ratios as the comparative values of jointed plates of equal sections when acted upon by a force calculated to tear them asunder.

The correct value of the plates, computed from a sectional area taken through the rivet-holes, will therefore be to their riveted joints as 100, 93 and 73, or in round numbers as 10, 9 and 7.

In addition to a loss of nearly one-tenth in the double-riveted joints, and three-tenths in the single ones, it will be observed that the strength of the plates is still further reduced by the quantity of iron punched out for the rivets.

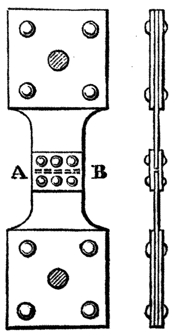
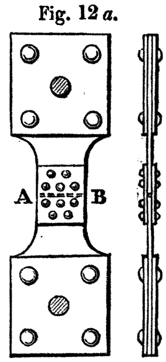
Table XI. Single riveted Plates.

No. of exp.	Description of plates and mode of riveting.	Weight laid on in lbs.	Changes produced by weight.	Breaking weight in lbs.	Form of specimen and mode of fracture.	Remarks.
40.	Plates same as before, ·22 inch thick, with overlap joint and double rivets; countersunk on one side; AB = $3\frac{1}{8}$ inches; five rivets, each $\frac{3}{8}$ diameter.	19,675	Plates bent in a right line; doubtful whether the joint would hold water	23,707	Fig. 11. 	By the word countersunk is understood a conical recess on one side of the plate to receive the head of the rivet, in order that it might not project beyond the surface of the plate. Tore across the three rivet-holes.
41.	Plates the same strength, but different from the last in having only $\frac{3}{8}$-inch rivets all in a line; AB = $3\frac{1}{8}$ ins.	14,839	Plates bent into a right line with the fixing......	16,351		In an unsuccessful experiment made before this upon plates precisely the same, and riveted in the same manner, they were torn across the rivet-holes in attempting to lay on 18,667 lbs. Plates tore across the rivet-holes.
42.	Same as last, except in not having the rivet-holes countersunk; lap $1\frac{1}{2}$ inch; AB = $3\frac{1}{8}$ inches	14,839	Joint sound............	16,351		All the rivets on one side were cut in two in the middle, and the plates left sound.

The results in the two last experiments, in the above Table, are identical as to strength. In the first, with the countersunk rivets, the plates were torn asunder, and in the latter the rivets appear the weakest, owing to the increased sectional area of the plates, which in the preceding experiment was reduced by countersinking the rivets.

In both experiments it will be observed that the strengths of the rivets are proportional to the strengths of the plates, their powers of resistance being equal, or nearly so. In forty-one experiments the sectional area of the rivets was to that of the plates as ·340 to ·347, that is, the sections were nearly equal; and in forty-two experiments as ·34 to ·44, which accounts for the nature of the fracture in both cases.

TABLE XII. Strength of riveted Plates.

No. of exp.	Description of plates and mode of riveting.	Weight laid on in lbs.	Changes produced by weight.	Breaking weight in lbs.	Form of specimen and mode of fracture.	Remarks.
43.	Plates the same as before, their edges brought into contact, and each plate riveted by three rivets $\frac{3}{8}$ of an inch diameter, to a plate on each side of the joint, each external plate being half the thickness of the internal, or a little thicker; AB $=3\frac{1}{4}$ ins.	19,879 24,715	Sound; no alteration.	25,723	Fig. 12. 	Both side plates were torn across, and two of the rivets cut off. The sum of the thickness of the side plates was ·24 inch, the middle plates being ·22 inch thick. The middle plates were left sound.
44.	Plate same as last ...	......	....	21,355 } Mean 23,539		Second experiment broken as before, the two outside plates torn off; all the rest sound.
45.	Same as the last experiment, having thicker plates outside, each being ·15 inch thick.	23,371	Joint good	24,715	Fig. 12 *a*. 	Middle plate torn straight across the rivet-holes. All the rivets and both plates left sound.
46.	Differing from the last only in having five rivets to each plate in double rows instead of three rivets $\frac{3}{8}$ diameter; AB $=3\frac{1}{4}$ inches...	23,371 25,387	Joint sound.........	 26,059		Both outside plates torn across at the three rivets.
47.	Same as the last	23,371 24,715	Joint sound......... Slightly altered; joint good	27,403 } Mean 26,731		Outer plate sound; torn across the two rivet-holes. Rivets sound; inner plate only torn.

When the comparative merits of plates and their riveted joints were under consideration, it appeared desirable to repeat several of the experiments, particularly those which seemed to throw light upon their relative powers of resistance. I considered these experiments to be of importance, as they increased our knowledge, as respects the strength of the material, and also its properties in combination.

In ship-building these objects are of some value, as any reduction in the powers or parts of a vessel by imperfect construction, or misapplied material, might lead to serious error and even great risk to the safety of the ship.

Since the first use of iron for these objects, it has been the practice to countersink the heads of the rivets in order to present a smooth surface for the passage of the vessel through the water. This practice is in general use at my works at Millwall, and I believe the same methods are pursued at the establishment of Messrs. JOHN LAIRD and Co., and others in different parts of the country. The introduction of this system of riveting caused a further extension of the experiments, in order to elucidate the various forms of joints given in the preceding Tables, and further to investigate the strength of the joint with a plate riveted on each side, which appears to be the strongest and best calculated to resist a tensile strain. This description of joint is seldom used in ship-building, but in order to render the experiments as perfect as

possible, it will be necessary to consider it in this paper with others of equal importance and probably of more general use.

The system of countersinking the rivets is only used when smooth surfaces are required; under other circumstances their introduction would not be desirable, as they do not add to the strength of the joint, but to a certain extent reduce it. This reduction is not observable in the experiments, but the simple fact of sinking the head of the rivet into the plate and cutting out a greater portion of metal, must of necessity lessen its strength, and render it weaker than the plain joint with raised heads. This must appear evident from the fact of the sectional area of the plate being diminished, and the consequent reduction of the heads of the rivets, which in this state are less able to sustain the effects of an oblique or transverse strain.

It is, however, satisfactory to observe that countersinking the heads of the rivets does not seriously injure the joint in its powers of resistance to a direct tensile force; but the rivets are liable to start when exposed to collisions or a strong impinging force, such as the sides of ships are frequently doomed to encounter.

On referring to experiments (Table XI.), the same results as to strength are obtained with the countersunk rivets as those with rounded heads; they are rather under the mean of the former experiments, but not more than is easily accounted for by the reduced section of the countersunk plates.

The joint with plates, riveted on each side, is seldom used, a circumstance which probably arises from its greater complexity of form and the danger which a treble thickness of plate would be subject to if used in boilers or vessels exposed to the action of intense heat. It is also inadmissible in ship-building, as the smooth surface requires to be maintained, and the greatest care observed in the formation of the outer sheathing to lessen the resistance of every part of the hull immersed in the water. In other respects the double-riveted plate is a strong joint, and in every case, where great strength is required, it may be used with perfect safety.

It will be unnecessary to go through a further comparison of the experiments, as sufficient data have already been furnished to enable us to calculate the force per square inch, and to resolve the whole into a general summary exhibiting the relative strengths—1st, of the plates; 2ndly, of the single- and double-riveted joints; and lastly, the ratio of the strengths as deduced from the whole series of experiments.

General summary of Results as obtained from the foregoing Experiments.

	Cohesive strength of plates. Breaking weight in lbs. per square inch.	Strength of single-riveted joints of equal section to the plates, taken through the line of rivets. Breaking weight in lbs. per square inch.	Strength of double-riveted joints of equal section to the plates, taken through the line of rivets. Breaking weight in lbs. per square inch.
	57,724	45,743	52,352
	61,579	36,606	48,821
	58,322	43,141	58,286
	50,983	43,515	54,594
	51,130	40,249	53,879
	49,281	44,715	53,879
	43,805	37,161	
	47,062		
Mean ...	52,486	41,590	53,635

The relative strengths will therefore be,—

For the plate 1000
Double-riveted joint 1021
Single-riveted joint 791

From the above, it will be seen that the single-riveted joints have lost one-fifth of the actual strength of the plates, whilst the double-riveted have retained their resisting powers unimpaired. These are important and convincing proofs of the superior value of the double joint, and in all cases where strength is required this description of joint should never be omitted.

On referring to the experiments contained in the separate tables, there will be found a striking coincidence in the facts tending to establish the principle of double riveting as superior in every respect to the general practice now in use of the single rivets. It appears, when plates are riveted in this manner, that the strength of the joints is to the strength of the plates of equal sections of metal as the numbers,—

1000 : 1021 and 791*.

In a former analysis it was 1000 : 933 and 731,

which gives us a mean of 1000 : 977 and 761

which in practice we may safely assume as the correct value of each. Exclusive of this difference, we must however deduct 30 per cent. for the loss of metal actually punched out for the reception of the rivets, and the absolute strength of the plates will then be, to that of the riveted joints, as the numbers 100, 68 and 46. In some cases, where the rivets are wider apart, the loss sustained is however not so great;

* The cause of the increase of strength in the double-riveted plates may be attributed to the riveted specimens being made from the best iron, whereas the mean strength of the plates is taken from all the irons experimented upon, some of inferior quality, which will account for the high value of the double-riveted joint. In ordinary cases and in practice it will therefore be safer to take the mean of the whole, viz.—

Strength of plates.................................. 100
Strength of double-riveting........................ 97
And of single-riveting 76

but in boilers and similar vessels, where the rivets require to be close to each other, the edges of the plates are weakened to that extent. In this estimate we must however take into consideration the circumstances under which the results were obtained, as only two or three rivets came within the reach of experiment: and again, looking at the increase of strength which might be gained by having a greater number of rivets in combination, and the adhesion of the two surfaces of the plates in contact, which in the compressed rivets by machine is considerable, we may fairly assume the following relative strengths as the value of plates with their riveted joints:—

Taking the strength of the plate at	100
The strength of the double-riveted joint would then be . .	70
And the strength of the single-riveted joint	56

These proportions may therefore in practice be safely taken as nearly the standard value of joints, such as used in vessels where they are required to be steam- or water-tight, and subjected to pressure varying from 10 to 100 lbs. upon the square inch.

Since the above was written, I have ascertained, on a recent visit to Bristol, that the large steam-ship* now building there is double-riveted, the plates being three-fourths of an inch thick over the bottom and bilge, and five-eighths thick up to the water-line. These plates are joined together with double rivets of 1 inch diameter, and inserted at distances of 3 inches apart. The proportions appear to be good; and conceiving the workmanship to be equally so, I should infer that this fine vessel would fairly establish the principle, that iron, in all the ramifications of ship-building, is an article of paramount importance to the war as well as to the mercantile navy.

In the pursuit of the foregoing inquiry, I was naturally led to the consideration of the best proportions and best forms of riveting plates together. I investigated this subject with great care, and from my own personal knowledge and that of others, I have collected a number of practical facts, such as long experience alone could furnish. From these data I have been enabled to complete the following Table, which for practical use I have found highly valuable in proportioning the distances and strength of rivets in joints requiring to be steam- or water-tight.

Table exhibiting the strongest forms and best proportions of riveted joints as deduced from the experiments and actual practice.

Thickness of plates in inches.	Diameter of rivets in inches.	Length of rivets from the head in inches.	Distance of rivets from centre to centre in inches.	Quantity of lap in single joints in inches.	Quantity of lap in double-riveted joints in inches.
$\cdot19=\frac{3}{16}$	·38 }	·88 }	1·25 } 6	1·25 } 6	For the double-riveted joint, add two-thirds of the depth of the single lap.
$\cdot25=\frac{4}{16}$	·50 } 2	1·13 }	1·50 }	1·50 }	
$\cdot31=\frac{5}{16}$	·63 }	1·38 }	1·63 } 5	1·88 }	
$\cdot38=\frac{6}{16}$	·75 }	1·63 } 4·5	1·75 }	2·00 } 5·5	
$\cdot50=\frac{8}{16}$	·81 }	2·25 }	2·00 }	2·25 }	
$\cdot63=\frac{10}{16}$	·94 } 1·5	2·75 }	2·50 } 4	2·75 } 4·5	
$\cdot75=\frac{12}{16}$	1·13 }	3·25 }	3·00 }	3·25 }	

* The Great Britain steam-ship.

The figures 2, 1·5, 4·5, 6, 5, &c. in the preceding Table are multipliers for the diameter, length and distance of rivets, also for the quantity of lap allowed for the single and double joints. These multipliers may be considered as proportionals of the thicknesses of the plates to the diameter, length, distance of rivets, &c. For example, suppose we take three-eighth plates and required the proportionate parts of the strongest form of joint, it will be—

$\cdot 375 \times 2 = \cdot 750$ diameter of rivet, $\frac{3}{4}$ inch.
$\cdot 375 \times 4\frac{1}{2} = 1\cdot 688$ length of rivet, $1\frac{3}{4}$ inch.
$\cdot 375 \times 5 = 1\cdot 875$ distance between rivets, $1\frac{3}{4}$ inch.
$\cdot 375 \times 5\frac{1}{2} = 2\cdot 063$ quantity of lap, 2 inches.
$\cdot 375 \times 5\frac{1}{2} = 3\cdot 438$ quantity of lap for double joints, $3\frac{1}{2}$ inches.

·75, 1·68, 1·87, 2·06 and 3·43 are therefore the proportionate quantities necessary to form the strongest steam- or water-tight joints on plates three-eighths of an inch thick.

In the preceding pages I have endeavoured to investigate almost every circumstance having a practical bearing on the question of the strength of rolled plates, and the best methods of uniting them together. In conclusion, I would venture a few remarks on the value and judicious use of this material, in its adaptation to ship-building, and other purposes to which it may be successfully applied. It is not my intention to enter into the question as to whether wood or iron be the preferable material, as a number of circumstances, such as cost, durability, &c., must be considered in order to form a correct decision.

I would however observe, that in ship-building alone, it appears from the facts already recorded, that iron is very superior in its powers of resistance to strain; it is highly ductile in its character, and easily moulded into any required form without impairing its strength. It is also stronger in combination than timber, arising from the nature of the construction, and the materials composing the iron ship become a homogeneous mass when united together, forming as it were a solid, without joints, and presenting as a whole the most formidable powers of resistance*. These are some of the properties which appear to distinguish iron from other materials, and which give it an ascendency of combined action, which cannot be obtained in the union of timber however ingeniously contrived. It moreover possesses the property of lightness along with strength; in fact, its buoyancy, strength and durability constitute the elements of its utility in the innumerable cases to which it may be applied. In ship-building it possesses other advantages over timber. Its hull is free from the

* Since the above was written we have had many examples of the enormous strength of iron ships, and amongst others we may instance an iron vessel which took the ground with nearly one-half of her length at the stern hanging over a shelf for a whole tide; another, the Vanguard iron steamer, which for several hours (under the action of a heavy surf) was beating upon sharp shelving rocks without going to pieces; and lastly, the Great Britain steam-ship, which was stranded in Dundrum Bay, and resisted the force of the winter storms for many months.

risk of fire; and in case of shipwreck, either on rocks or sand-banks, it will resist the heaviest sea, endure the severest concussion, and with proper attention to the construction, it may be the means of saving the lives of all on board. It moreover has the advantage of bulkheads, which, made perfectly water-tight, not only strengthen the vessel, but give greater security to it, and by a judicious arrangement in the divisions will float the ship under the adverse circumstance of a leak occurring in any one of the compartments. These are the qualities and powers of the iron ship; and I trust the present research into the strength and proportions of the material of which it is composed, will not only give increased confidence in its security, but will lead to an extension of its application in every branch of marine and mechanical architecture.

PART III.

Resistance of Wrought-iron Plates to Pressure by a Blunt Instrument at right angles to the surface of the Plate.

Irrespective of the experiments made to determine the strength of wrought-iron plates and the relative strength of the joints by which they are united, the investigation would be incomplete if we omitted another inquiry of equal importance, namely, the resistance offered by plates to a crushing force, such as exhibited in the injuries received by vessels when stranded on rocks or taking the ground in harbours where the surfaces are uneven.

Almost every person connected with nautical affairs is acquainted with the nature of the injuries received by timber-built vessels when placed in circumstances affecting their stability, or when resting on hard and unequal ground, such as frequently occurs in tidal harbours at low water. Such a position is attended with danger under every circumstance; and in order to determine the relative values of the two materials, wood and iron, it was considered desirable to institute a similar class of experiments on both, and thus to afford the means of comparison between them. English oak, as the strongest and best material used for the construction of first class vessels, was selected for this purpose, and the results obtained from both are given, under circumstances as nearly similar as the nature of the experiment would admit. They are as follows.

In each of the experiments the plate was fastened upon a frame of cast iron, 1 foot square inside and 1 foot 6 inches outside, its breadth being 3 inches and thickness half an inch. The sides of the plates, when hot, were twisted round the frame, to which they were firmly bolted. The contraction, by cooling, caused it to be very tight, and the force to burst it was applied in the centre. This was done in order that the force might in some degree resemble that from a stone or other body with a blunt end pressing against the side or bottom of a vessel: a bolt of iron, terminating in a hemisphere 3 inches in diameter, had thus its rounded end pressed perpendicularly to the plate in the middle. The results are given in the following Tables.

TABLE XVI

Fig. 17.

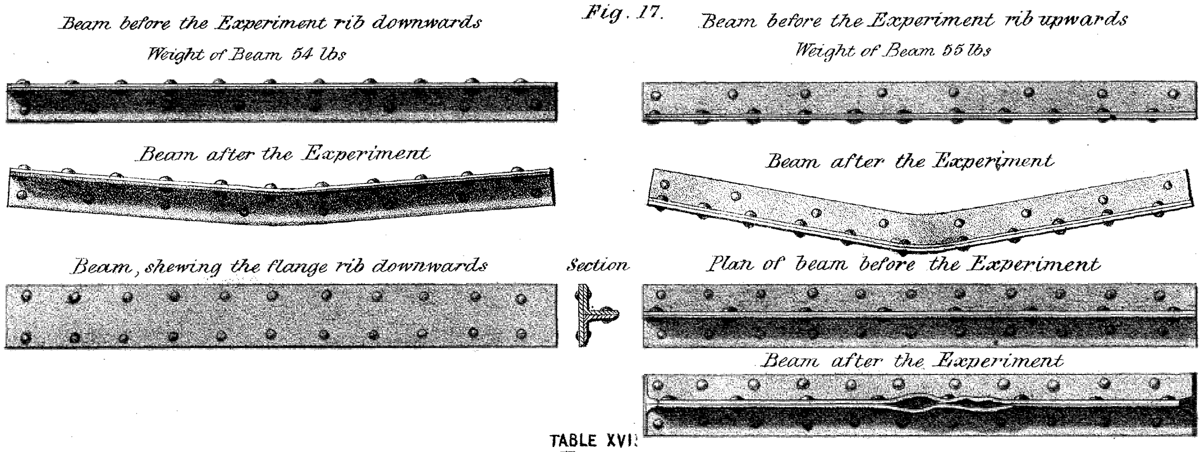


TABLE XVII

Fig 18

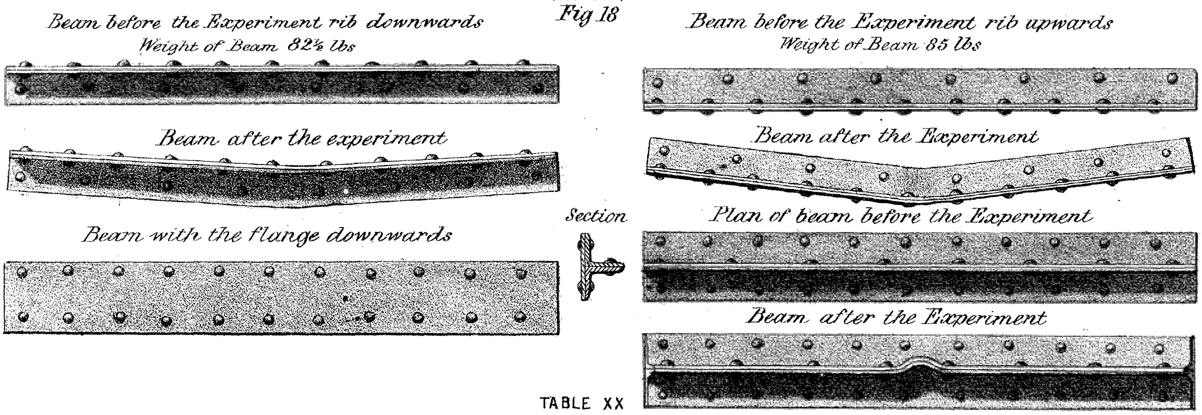


TABLE XX

Fig. 19.

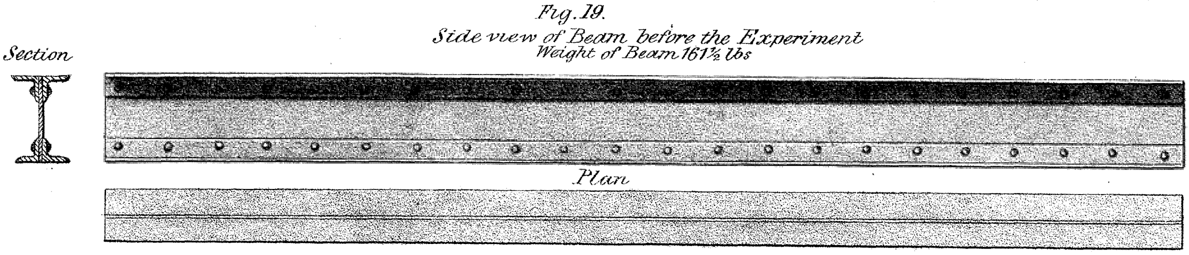


TABLE XIII

Fig. 13.

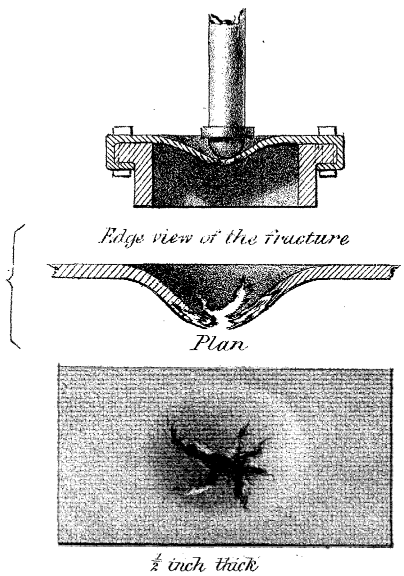
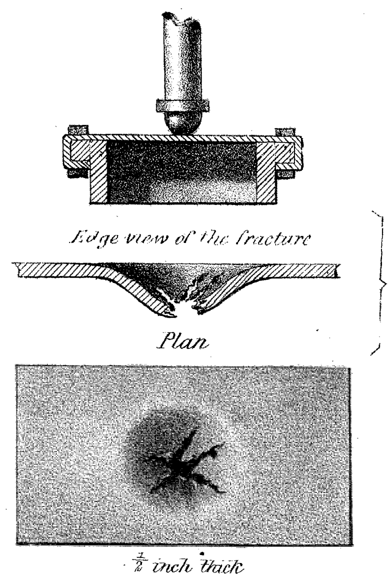


Fig. 14.



J. Basire, Lith.

TABLE XIII. Experiments to determine the Resistance of Plates of Wrought Iron to a force tending to burst them.

No. of exp.	Description of plates.	Weight laid on in lbs.	Permanent indentation of plate.	Remarks.
			inch.	
1.	Plate of the best Staffordshire iron $\frac{1}{4}$ inch thick.	8,617	·3	Plate not cracked.
		9,893	·35	Plate not cracked.
		11,169	·5	Crack on convex side 8 inches long.
		12,445	·6	Crack on convex side 9 inches long; not opened on concave side.
		13,789	·7	Hole through the plate about $1\frac{1}{2}$ inch long, and $\frac{1}{8}$ inch wide.
2.	Plate of the same iron and the same thickness.	9,893	·25	Double crack on convex side 1 inch long.
		11,169	·34	Double crack increased.
		12,445	·4	
		13,789	·47	
		16,477	·6	Form of crack on convex side ($\frac{1}{8}$ inch wide).
		17,821	·65	Not cracked through.
		19,769	......	Cracked through.
3.	Plate of the same iron $\frac{1}{2}$ inch thick.	18,523	......	No crack.
		21,075	·33	Incipient crack on convex side.
		22,787	·45	Crack above-mentioned 4 inches long, forming a cross.
		25,923	·60	Crack above, 6 inches long.
		29,059	·75	Crack above, $\frac{1}{8}$ inch wide.
		32,195	·80	
		35,331	·97	
		36,899	1·10	No crack on concave side.
		37,519	......	Plate cracked through.
4.	Plate same as the last.	21,219	......	No crack.
		21,985	·35	Slight crack on convex side.
		27,708	·47	Form of crack on convex side.
		31,796	·7	Form of crack increased.
		33,431	·75	
		35,066	·83	Form of crack 4 inches deep.
		36,701	·97	Not cracked through.
		37,928	......	Cracked through.

In Plate LVIII. figs. 13 and 14, will be found representations of the fractures of the plates experimented upon in this Table.

From the above we obtain the strength of plates to resist rupture from pressure from a blunt body, or a ball 3 inches diameter.

	lbs.	Mean.
In experiment 1, a plate one-fourth of an inch thick was burst by	13,789	16,779
In experiment 2, a plate one-fourth of an inch thick was burst by	19,769	
In experiment 3, a plate half an inch thick was burst by . . .	37,519	37,723
In experiment 4, a plate half an inch thick was burst by . . .	37,928	

Here the strengths are as the depths, a half-inch plate requiring double the weight to produce fracture that had previously burst the quarter of an inch plate. In the succeeding experiments on oak timber, the powers of resistance follow the ratio of the squares of the depth, so that a wrought-iron plate of only one-quarter of an inch thick is able to resist a force equal to that required in the rupture of a 3-inch plank.

The experiments were made upon good English oak, of different thicknesses, and of the same width as the iron plates. The specimens were laid upon solid planks, 12 inches asunder, and by the same apparatus the rounded end of the 3-inch pin was forced through them as follows:—

Resistance of planks of timber to the entrance of a ball, 3 inches diameter, the planks being laid upon props 12 inches asunder; the object of the experiments being to burst them by pressing a pin, terminated by a hemispherical end, 3 inches diameter, through the centre of the plank, as was done with the plates of iron.

TABLE XIV.

No. of exp.	Description of plank.	Weight laid on.	Remarks.
		lbs.	
1.	English oak, very dry and good, 11¾ inches broad, and 2½ inches deep.	16,115 17,235	Indentation from hemisphere ½ inch deep; wood otherwise uninjured. Hole through the middle, 3 inches diameter nearly broke out, all the rest remaining sound.
2.	English oak, rather green, 8 inches broad, 3 inches deep.	18,941	It bore 18,941 lbs. about ten minutes, and then exploded with violence, dividing into three parts, the middle one on which the pin rested being about an inch thick at the top, and ½ an inch at the bottom. With a ton less weight there was a crack under the plank in the centre, and an indentation by the pin ½ inch deep on the upper side. Sap was driven out from the ends on the side nearest to the heart.
3.	English oak plank, and dimensions same as in last experiment.	12,445 16,925	Sap driven out as in last experiment; plank without crack; indentation by the pressure about ½ inch. The plank split with bearing the pressure about ten minutes.
4.	English oak from same plank as in experiment 2 and 3; breadth 8 inches, depth 1½ inch.	4,532	The plank broke by splitting.
5.	English oak from same plank and same size as in the last experiment.	4,280	Broke by splitting diagonally.

Taking the results of the four last experiments, which were on pieces from the same plank, we obtain—

	lbs.	Mean.
Strength from planks 3 inches thick	18,941	17,933
Strength from planks 3 inches thick	16,925	
Strength from planks 1½ inch thick	4,532	4,406
Strength from planks 1½ inch thick	4,280	

Here the strength to resist crushing follows the ratio of the square of the depth, as is found to be the case in the transverse fracture of rectangular bodies of constant breadth and span.

If we compare the foregoing results with the experiments performed by Mr. HODGKINSON on timber, it will be found that the strength of dry English oak to resist a crushing force is 4·24 tons to the square inch, whereas wrought iron, according to RONDELET, requires a pressure of about 31 tons per square inch, and with this weight it is reduced about one-sixteenth of its length. The resistance of wrought iron to a crushing force is therefore about seven and a quarter times greater than that of oak: and according to the experiments in the preceding Table, it appears that the resistance of wrought-iron plates to a force calculated to burst them, follows a different law to that of oak, the resistance of the former being directly as the depth and of the latter as the square of the depth. Reasoning from these facts, it may be interesting to know that in the use of timber, such as the oak sheathing of ships, the strength to ex-

ternal pressure increases in the ratio of the squares of its thickness; and, where great strength is required, it will be necessary, in the construction of vessels, to consider the nature of the service and the required thickness of the planks.

The same remarks will apply to vessels constructed of iron, computed from the formula deduced from the experiments. In a table of experimental results by Mr. Hodgkinson we have the mean force per square inch required for crushing timber of different kinds; and assuming Rondelet's experiments, which give 70,000 lbs. as the resistance per square inch of wrought iron, to be correct, we then have as the ratio of their respective powers of resistance as follows:—

Table XV.

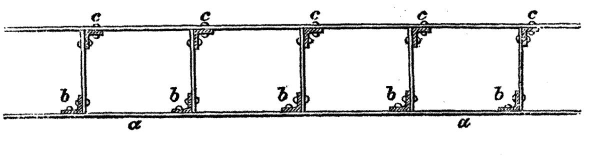
Specific gravities.	Description of timber used.	Resistance per square inch.	Resistance of wrought iron per square inch.	Ratio, the wood representing unity.
		lbs.	lbs.	
7·700	Wrought iron	......	70,000	
0·560	Yellow pine............	5375	70,000	1 : 13·02
0·540	Cedar	5674	70,000	1 : 12·33
0·580	Red deal	5748	70,000	1 : 12·16
0·640	Birch	6402	70,000	1 : 10·93
0·660	Sycamore..............	7082	70,000	1 : 9·88
0·753	Spanish mahogany ...	8198	70,000	1 : 8·53
0·780	Ash	8683	70,000	1 : 8·06
0·700	Dry English oak......	9509	70,000	1 : 7·36
0·980	Box	9771	70,000	1 : 7·16

In addition to the relative resisting forces of the different kinds of timber above enumerated, will be found the specific gravities of each, which enables the reader to determine the comparative weights as well as strength of the different kinds of wood.

PART IV.

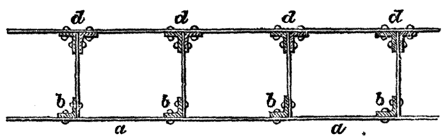
In the preceding researches I have endeavoured to determine the value of iron chiefly in reference to its application for the purposes of ship-building. It now only remains to determine the best form and condition of another part of the structure, namely, the frames and ribs of vessels, also composed of iron. Some of the forms experimented upon indicate weakness, but certain modifications which have since been introduced, have given increased support to the bilge and sides of the ship, and greater powers of resistance to the outer sheathing. The beam shown at fig. 19, Plate LVIII., is probably one of the strongest and most suitable for the support of the decks, but it is inadmissible as a frame for receiving the exterior sheathing plates. These frames are generally formed of a plate with angle-irons along the edges on both sides, of which the annexed sketch are sections. *a*, *a*, &c. represents a portion of the outside plates; *b*, *b* the angle-iron frames or ribs, which vary from 18 to 24 inches asunder, according to the position in the direction

Fig. 15.



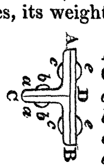
of the length of the ship; *c*, *c*, angle-iron of the same strength is riveted along the edge of each rib for the purpose of stiffening the sides of the ship and giving increased resistance to those parts, also to receive interior plates, some of which, in large vessels, are riveted diagonally to the interior angle-irons *c*, *c*, &c., forming stringers and braces from the kelsons round the bilge to the upper decks.

Fig. 16.



Other kinds of frames might be used with double angle-iron, as shown at *d*, *d*, &c. in the annexed sketch, but they are more expensive, and from the increased complexity of construction, the extra strength obtained does not compensate for the difference of cost. Altogether, the frames recorded in fig. 15 have come into general use as the most effective and easy of construction. Those experimented upon were of different kinds, as shown in Plate LVIII. fig. 17, 18, &c., and in sections given in the Tables, and from which the following results were obtained:—

Table XVI. Experiments to ascertain the strengths of uniform wrought-iron beams of different forms to support the sides and other parts of vessels, the beams having their ends placed upon props and being loaded in the middle.

No. of exp.	Description and form of the beam.	Weight laid on middle.	Deflections with these weights.	Breaking weight of the beam of 7 feet between the supports.	Weight of the beam of 7 feet 6 inches long.	Oak beams. Side of square of oak beams of equal strength with the iron one.	Oak beams. Weight of such beams of 7 feet 6 inches long and specific gravity 900.	Remarks.
		lbs.		lbs.	lbs.	inches.	lbs.	
1.	Beam formed from two 2½ angle-irons, riveted together with rivets 6 inches asunder, and a plate a ¼ inch thick riveted to the back, with rivets 4 inches asunder. Distance between the supports 7 feet, and whole length 7 feet 6 inches, its weight being 109 lbs. Dimensions of section.  Thickness. AB = 5 inches. CD = 2·6 inches. *aa* = ·5 inch. *bb* = ·56 inch. *cc* = ·64 inch. *ee* = ·25 inch. The part C was downwards during the experiment, the weight being laid upon the part D.			3355	109	3·6324	38·65	The weight 3355 lbs. was laid on at once, and the beam almost immediately sunk with it; a weight something less would have done it.
2.	The beam last used, cut in two; distance between supports 2 feet 3 inches; vertical rib downwards, that it might be stretched as before; weight of 3 feet 9 inches = 54 lbs.	4,039 5,383 6,055 6,727 7,399 7,735 sunk	·18 ·30 ·43 ·64 ·88	2486	109	3·287	31·80	With 7735 lbs. it sunk, by stretching and tearing at a rivet-hole.
3.	The other half of the beam (exp. 1.) cut in two. Distance between the supports 2 feet 3 inches; weight of 3 feet 9 inches = 55 lbs.; vertical rib upwards thus, ⊥ that fracture might take place by the compression of that rib.	4,039 5,383 6,055 6,727 7,399 8,071 8,743 9,415 10,087 10,423 10,759 sunk	·17 ·23 ·26 ·34 ·47 ·63 ·85 1·10 1·95 2·90	3458	109	3·6692	39·44	With 10,759 lbs. it sunk; the vertical rib becoming twisted.

All the beams experimented upon in the foregoing Table are shown in view and in section, Plate LVIII. figs. 17 and 18. In the first experiment the beam was 7 feet between the supports, but having yielded to the first weight, 3355 lbs., laid on, it was subsequently cut in two, as shown in the drawings above referred to. In experiment 2, it will be observed that a frame of this form is weak, arising from the deficiency of material on the lower side of the rib formed by angle-iron, which, yielding to a tensile strain, becomes elongated in the act of bending, and would thus deflect through a considerable space before actual fracture took place. Reversing the other part of the beam with the broad flange downwards it carried more weight, but ultimately sunk under a load of 10,759 lbs., being in the ratio of 10 : 7 in favour of the beam with the rib upwards.

These experiments, when reduced to 7 feet between the supports, gave nearly the same proportion, viz. nearly as 34 : 24. They are however all weak, arising almost exclusively from want of material on the top edge of the ribs, and a due proportion in the construction of the beam.

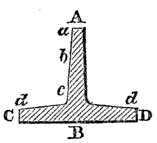
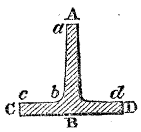
TABLE XVII. Experiments on Wrought-iron Beams (continued).

No. of exp.	Description and form of the beam.	Weight laid on middle.	Deflections with these weights.	Breaking weight of the beam of 7 feet between the supports.	Weight of the beam of 7 feet 6 inches long.	Oak beams. Side of square of oak beams of equal strength with the iron one.	Oak beams. Weight of such beams of 7 feet 6 inches long and specific gravity 900.	Remarks.
		lbs.		lbs.	lbs.	inches.	lbs.	
4.	Beam differing from that in exp. 1 only in being of greater strength, this beam being formed of two 3-inch angle-irons, riveted as before to a plate a ¼-inch thick. Distance between the supports 7 feet; weight of the beam 7 feet 6 inches long, 167½ lbs.; vertical rib downwards ┬.	3,355 4,711 5,383 5,719 6,055 6,391 6,727 ...... 7,063 7,399	·40 ·62 ·82 ·98 1·12 1·30 1·87 1·92 2·29 3·25	7399	167·5	4·7281	65·49	After bearing the weight 7399 lbs. a short time the beam became cracked at a rivet-hole and sunk. From the experiments of BUFFON upon green oak, the side of a square beam of equal strength would be 4·558 inches, and its weight 708 lbs.
5.	Half the beam used in exp. 4, now 3 feet 9 inches long, and weighing 82½ lbs. Distance between supports 3 feet 6 inches; vertical rib downwards.	4,039 7,399 10,759 11,431 12,103 12,439	0·85 0·25 0·43 0·53 0·65 broke at a rivet-hole.	6219	1675	4·462		
6.	The other half of the beam in exp. 4, weighing 85 lbs.; length 3 feet 6 inches. Distance between the supports 2 feet 3 inches; rib upwards ┴.	8,304 12,392 16,480 18,115	0·12 0·24 0·75 sunk, the vertical rib being twisted.	5823	1675	4·3653	55·83	

The whole of the experiments herein recorded are of the same description as the last, with the exception of the beam being composed of thicker angle-iron, and consequently rendered much stiffer and stronger than those first experimented upon. This increased stiffness reversed the resisting powers of the beam, when taken at a 7-feet

span, in the ratio of 6 : 5 in favour of the first position with the rib downwards. For plans and sections of these beams see Plate LVIII. fig. 18.

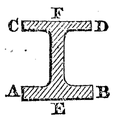
Table XVIII. Experiments on Wrought-iron Beams (continued).

No. of exp.	Description and form of the beam.	Weight laid on middle.	Deflections with these weights.	Breaking weight of the beam of 7 feet between the supports.	Weight of the beam of 7 feet 6 inches long.	Oak beams. Side of square of oak beams of equal strength with the iron one.	Oak beams. Weight of such beams of 7 feet 6 inches long and specific gravity 900.	Remarks.
		lbs.		lbs.	lbs.	inches.	lbs.	
7.	Solid wrought-iron beam, 4 feet 2 inches long, weighing 23 lbs., placed upon props 4 feet asunder; vertical rib upwards. Form and dimension of section.  Thickness at a = ·24 b = ·29 c = ·41 d = ·36 AB = 2·50 CD = 2·85	1394 1932 2470 2739 3008	·135 ·24 ·59 ·90 1·35	1790	41·4	2·9461	25·43	With 3008 lbs. the elasticity was entirely destroyed, and a like additional weight would have destroyed the form of the beam.
8.	Same beam rendered straight, and turned with its rib downwards ⊤.	1394 1932 2470 2739 3008 3142	·17 ·25 ·66 1·22 2·20 sunk	1870	41·4	2·9894	26·18	
9.	Solid beam, same form as before; length 5 feet ⅜ inch; weight 25¼ lbs. Distance between supports 4 feet; rib upwards thus. See fig. to experiment 7.  Thickness at a = ·23 b = ·30 c = ·40 d = ·33 AB = 2·05 CD = 2·95	1394 1932 1526 2201 2335 in a few minutes	·30 ·86 1·19 1·59 2·04 2·13	1334	37·6	2·671	20·90	After bearing the weight, 2335 lbs., it had taken a permanent set, or flexure = 1·71 inch, and would have sunk more if it had not been unloaded.
10.	Same beam rendered straight and turned upside down thus ⊤. Distance between supports 4 feet.	1394 1932 2201 2335 in a minute 2469	·27 ·51 1·01 1·57 1·60 2·50	1411	37·6	2·7215	21·70	After bearing 2469 lbs. it was unloaded, as a little additional weight would have destroyed its form.

The experiments in this Table were made on solid ⊤ iron, and indicate nearly the same proportions, as respects their strength, as the beams composed of a plate and double angle-iron riveted together. The whole of these beams appear to be defective in form, and are therefore not calculated to sustain a severe transverse strain. To attain the section of greatest strength, it is probable a different form would be required, as well as a different proportion of the parts, such as in the annexed figure with a double flange*.

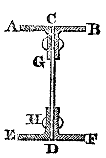
* Since the experiments herein recorded were made, others have been instituted on some deck-beams by Mr. Kennedy of Messrs. Bury, Curtis and Kennedy, Liverpool, the particulars of which are inserted in the Appendix.

TABLE XIX. Experiments on Wrought-iron Beams (continued).

No. of exp.	Description and form of the beam.	Weight laid on middle.	Deflections with these weights.	Breaking weight of the beam of 7 feet between the supports.	Weight of the beam of 7 feet 6 inches long.	Oak beams. Side of square of oak beams of equal strength with the iron one.	Oak beams. Weight of such beams of 7 feet 6 inches long and specific gravity 900.	Remarks.
		lbs.		lbs.	lbs.	inches.	lbs.	
11.	Beam of wrought iron, formed of two bars (nearly equal), whose section is riveted together; length of the beam 4 feet 2 inches; its weight 44 lbs. 5 oz. Distance between the supports 4 feet. Dimensions of section. AB = 2·86 inches. Mean thickness of AB = ·33 inch. EF = 3·70 inches. 	4,195	0·75					
		7,465	0·148					
		10,735	0·22					
		10,735 laid on again.	......	......	......	......	......	After bearing the weight 10,735 lbs., the beam had taken a set = ·06. Pieces of wood were driven tightly in between the ribs AB, CD, at each side of the beam in *the middle*, to prevent the load laid on it there from deranging its form. The beam broke by the bottom rib being torn asunder, preceded by one of the bars cracking at a rivet-hole.
		14,005	0·24 broke	8336	79·76	4·9199	70·91	

The above is probably the strongest form of beam, if duly proportioned, by adapting the material to a balance of the two opposing forces of extension and compression.

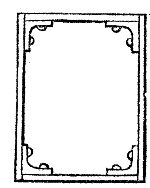
TABLE XX. Experiments on Wrought-iron Beams (continued).

No. of exp.	Description and form of the beam.	Weight laid on middle.	Deflections with these weights.	Breaking weight of the beam of 7 feet between the supports.	Weight of the beam of 7 feet 6 inches long.	Oak beams. Side of square of oak beams of equal strength with the iron one.	Oak beams. Weight of such beams of 7 feet 6 inches long and specific gravity 900.	Remarks.
		lbs.		lbs.	lbs.	inches.	lbs.	
12.	Beam of wrought iron composed of an uniform vertical rib (7 inches deep and 7 feet 6 inches long) with two 2-inch angle-irons riveted to both top and bottom of the rib; rivets 4 inches asunder; weight of beam $161\frac{1}{2}$ lbs. Distance between the supports 7 feet. Dimensions of section. CD = 7 inches. AB = 4·5 inches. EF = 4·5 inches. Mean thickness of AB = ·28 inch. EF = ·30 inch. Plate GH = ·25. 	4,216	·10					
		8,304	·18					
		16,480	·25					
		18,667	·36					
		22,027	·52					
		in five minutes	} ·54	24,379	$161\frac{1}{2}$	7·0358	145·03	
		24,379	sunk	......	......	......	......	With the weight 24,379 lbs. the top ribs of the beam became twisted.
13.	Same beam rendered straight and uniform; experiment 12 repeated.	16,115	·29					The beam was heated by the smiths, and when reduced to its original form, it was allowed to cool gradually.
		18,355	·36					
		19,475	·42					
		20,595	·51					
		21,715	sunk	21,715	$161\frac{1}{2}$	6·7695	134·26	With 21,715 lbs. it became bent, towards the wall, in a direction in which it was slightly drawn by the lever; ribs not twisted as before. It bore the weight a minute or two before giving way.

This experiment shows the superior quality of wrought-iron beams in giving timely notice before fracture; it further exhibits weakness on the top sides of the beams, a circumstance requiring great attention in their construction, which in some recent experiments, instituted for attaining the section of greatest strength, have been strikingly developed*.

In the preceding experiments, we have endeavoured to compare the strengths, as well as the weights of the beams or frames which form the ribs of ships. As regards the strengths with equal weights, it is in favour of oak; but the circumstance of the fastenings by rivets in the sheathing being so much superior to those of timber, the iron ship-builder is enabled to dispense with one-half the number of frames, and consequently a great reduction of weight is effected and more strength obtained in the vessel as a whole, than could possibly be accomplished in the timber-built ship, however ingenious the construction or the arrangement and distribution of the material. The very act of caulking the joints of a wooden vessel has a tendency to loosen the fastenings, whereas, in the iron ship, there are no actual joints, for the whole being bound together *en masse*, the same, or nearly the same, strength is obtained as if the whole ship were composed of solid plates and ribs.

The best sectional form of beams for the decks of ships is probably that exhibited in Table XX., which, along with the box beam of the annexed form for supporting the shafts and paddle-boxes of steamers, is that generally used in the construction of vessels of this description. Other forms have been adopted, particularly those suggested by Mr. Kennedy of Liverpool, alluded to in the Appendix.



Having carefully investigated the different properties of wrought iron in its varied forms of construction, and conceiving that the results obtained from the experiments may be useful in a variety of circumstances connected with the useful arts, I have endeavoured to collect them in the abstract, in order that the practical builder and engineer may the more readily ascertain the comparative value of the different forms of beams, the properties of the material, and their adaptation to any particular construction in which he may be engaged. Should further information be required, we must then refer to the experiments, in which will be found the facts more in detail, and which are probably better calculated to satisfy the inquiring mind and to effect that conviction essential to success.

I have not attempted any inquiry into the laws of oxidation, the adhesion of barnacles and marine vegetation, and the means necessary to prevent such evils. This is a subject which does not come within the province of the present inquiry, and more properly belongs to that of the chemist. I would however briefly notice, that in the whole of my experience I have had little to complain of from the effects of oxidation, as that destructive process, as regards iron, appears to be greatly mitigated, if not almost suspended, by constant use, and under the influence of vibratory action the operation appears to be rendered nugatory, if it does not entirely cease, and that

* See my work on the Construction of the Britannia and Conway Tubular Bridges.

under circumstances exceedingly difficult to explain. This is an investigation not unworthy the attention of some of our best chemists, to whom the causes may be known, but which are at present, as far as I know, unaccounted for. For example, I may mention that an iron ship, if kept constantly in use, or nearly so, will last for a number of years exposed to all the changes of weather and temperature without any sensible appearance of decay. The same may be said of iron rails, over which are passing daily such enormous weights, and at such velocities as almost to neutralize the action of the elements. All these are striking examples of the durability of wrought iron, which may be considered as an important element of its security, and a recommendation for its extended application. There is another circumstance in connection with this subject to which it may be necessary in this place to advert, and that is the effect which a long continuance in salt water has upon the hull of an iron ship. It is well known that a long immersion of cast iron in the sea will convert it into plumbago, and that a similar process with malleable iron, from its contact with the saline particles of the ocean, produces oxidation; and in case the immersions were long continued, the effects of this destructive process might endanger the safety of the ship. As yet we have not had sufficient evidence of its effects to enable us to come to any definite conclusion, but it is not improbable that an occasional visit to harbours of fresh water may mitigate, if it does not entirely neutralize, the injurious effects which the material is likely to sustain. With these observations, which I offer with diffidence, I now beg to direct attention to the abstracts as deduced from the experiments.

Abstract of Results as obtained from the experiments.

In Part I. of this inquiry we have endeavoured to show that 50,000 lbs. per square inch is the mean breaking weight of iron plates, whether torn asunder in the direction of the fibre or across it; and we have also shown that the tensile strength of different kinds of timber drawn in the direction of the fibre varies in a given ratio to that of iron: the timber in this comparison being represented by unity, we have the following ratio of strength:—

	Timber :	Iron.
Ash as	1 :	2·94
Teak as	1 :	3·33
Fir as	1 :	4·16
Beech as	1 :	4·34
Oak as	1 :	5·00

These, for practical purposes, may be taken as a fair measure of the strength of the different woods as compared with that of iron plates.

It has been shown that wrought-iron plates, when riveted together, lose a considerable portion of their strength, as may be seen by the experiments in Part IV., where the plates, by their union with each other, lose by the ordinary process of riveting 44 per cent., and by the best mode of riveting 30 per cent. This should not however

create serious alarm, as the loss of strength is almost entirely obviated by the new process of riveting used in the bottom of the Britannia and Conway Tubular Bridges*; and it should also be observed that in timber the same injuries are sustained by splicing or any other method of forming the joints as are here exhibited in the riveting of iron plates. The two processes, that of riveting (according to the method used in the experiments) and splicing, when intended to resist a tensile strain, must therefore be considered analogous, and the comparison under such circumstances will nearly follow the same law as regards a diminution of strength.

In this section of the inquiry the results obtained from the experiments indicate a loss in the joints as compared with the solid plate, as the numbers 100, 70 and 56, viz.—

For the solid plate	100
For the double-riveted joint	70
For the single-riveted joint	56

which numbers may be considered as a fair average value of the strengths of the different parts of vessels constructed in this manner.

Part V. exhibits the strength of plates to resist vertical pressure from a blunt instrument, which was forced through them for the purpose of ascertaining their comparative powers of resistance with oak timber, placed under circumstances precisely similar and subjected to the same force. The results are interesting, as the iron plates appear to follow a different law in their resistance to pressure to that of oak, the strength being as the depth or thickness of the plates in the first case, and as the squares of the depth in the second. The resistances are therefore in the ratio of 1 : 12, the iron being 12 times stronger than oak.

In Part IV. we have some curious facts illustrative of the necessity and value of experimental research. In the earlier experiments of the inquiry it is evident, that angle and T iron beams or frames are not the best, as regards form, to resist a transverse strain. In every case they are weak, and although exceedingly useful, and in fact indispensable for many purposes of construction, they are nevertheless not calculated to resist strain in the form of beams or girders. These defects I have endeavoured to obviate by the introduction of beams with double flanges formed of a body plate and riveted angle-irons at the top and bottom. All these latter constructions may however be left with safety to the practical engineer†.

The strengths of nearly the whole of these beams have been mathematically investigated by Mr. Tate, to whose friendship and analytical research I am indebted for the annexed mathematical inquiry into the different forms of the wrought-iron beams which have been experimented upon. To the mathematician this part of the subject will be the more interesting, as the utmost care has been observed in the measurements

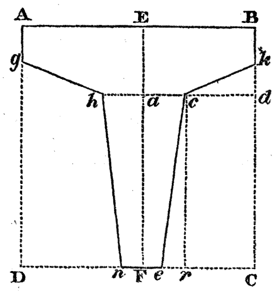
* See my process of chain-riveting as exhibited in the lower sides of the Britannia and Conway Tubular Bridges, where the injuries above enumerated are entirely obviated.

† For a more elaborate inquiry into the strengths of wrought-iron beams, see my work on the Britannia and Conway Bridges.

and exact proportions of the parts, in order to obtain the necessary formula for calculating the strength of beams and frames of this description.

FORMULÆ RELATIVE TO THE BEAMS IN THE FOREGOING EXPERIMENTS.

Beams with a Single Flanch.



Let ABF be a section of a beam having a single flanch ABkh, the material being symmetrically distributed with respect to the vertical line EF. Let $hacd$ and DFC be parallel to AB; cr and kdC parallel to EF. Put $EB=EA=e$, $CB=DA=e_1$, $ac=Fr=t$, $Bk=Ag=t_1$, $Ea=Bd=t_2$, $Fe=Fn=t_3$, area section AB$cenhg$=A, and the distance of the centre of gravity of this section from the edge ne=X.

To find the Position of the Neutral Axis.

Assuming the material to be perfectly elastic, the neutral axis will be in the centre of gravity of the section. Hence we have, by calculating the moments with respect to the line DC,

$$A\times X=ee_1^2-(e_1-t_2)^2(e-t)-\frac{1}{3}(e_1-t_2)^2(t-t_3)-(e-t)(t_2-t_1)\left(e_1-\frac{2}{3}t_2-\frac{1}{3}t_1\right),$$

$$\therefore\ X=\frac{3ee_1^2-(e_1-t_2)^2(3e-2t-t_3)-(e-t)(t_2-t_1)(3e_1-2t_2-t_1)}{3A}, \quad \ldots\ldots \quad (1.)$$

which expresses the distance of the neutral axis from the edge ne, where

$$A=(t+t_3)(e_1-t_2)+(t_1+t_2)(e-t)+2tt_2 \quad \ldots\ldots \quad (2.)$$

To find the Moments of Rupture.

Let I = the moment of inertia of the section about the neutral axis.

I_1= the moment of inertia of the section about DC.

W= the breaking weight of the beam.

l= the distance between the supports.

S= the force per square inch of the material opposed to extension or compression, as the case may be, at the thin edge of the beam.

Taking DC as the axis,—

I_1= moment inertia ABCD−2 moment inertia rCdc −2 moment inertia erc−2 moment inertia cdk.

Now, moment inertia ABCD$=\frac{2}{3}ee_1^3$,*

2 moment inertia rC$dc=\frac{2}{3}(e-t)(e_1-t_2)^3$,

2 moment inertia $erc=\frac{1}{6}(t-t_3)(e_1-t_2)^3$,

2 moment inertia $cdk=\frac{1}{6}(e-t)\{(e_1-t_1)^3-3(e_1-t_2)^3+(e_1-t_1)(e_1-t_2)(2e_1-t_1-t_2)\}$.

Substituting these values and reducing, we find

$$I_1=\frac{1}{6}\left[4ee_1^3-(e_1-t_2)^3(e-t_3)-(e-t)(e_1-t_1)\{(e_1-t_1)^2+(e_1-t_2)(2e_1-t_1-t_2)\}\right]\ldots \quad (3.)$$

Also (MOSELEY's Engineering, p. 82) we have

$$I=I_1-AX^2. \quad (4.)$$

Moreover, by the formula of rupture,

$$\frac{Wl}{4}=\frac{SI}{X},$$

$$\therefore \quad S=\frac{WlX}{4I}. \quad (5.)$$

Taking the data of Table XVI., we have

$$e=2{\cdot}5,\ e_1=2{\cdot}6,\ t={\cdot}32,\ t_1={\cdot}35,\ t_3={\cdot}25,\ t_2={\cdot}42\,;$$

therefore, by equation (2.),

$$A=({\cdot}32+{\cdot}25)(2{\cdot}6-{\cdot}42)+({\cdot}35+{\cdot}42)(2{\cdot}5-{\cdot}32)+2\times{\cdot}32\times{\cdot}42=3{\cdot}19.$$

By equation (1.),

$$X=\{3\times2{\cdot}5\times2{\cdot}6^2-(2{\cdot}6-{\cdot}42)^2(7{\cdot}5-{\cdot}64-{\cdot}25)-(2{\cdot}5-{\cdot}32)$$
$$\times({\cdot}42-{\cdot}35)(7{\cdot}8-{\cdot}84-{\cdot}35)\}\div3\times3{\cdot}19=1{\cdot}91,$$

which is the distance of the neutral axis from the edge *ne* of the beam.

By equation (3.),

$$I_1=\frac{1}{6}\left[4\times2{\cdot}5\times2{\cdot}6^3-(2{\cdot}6-{\cdot}42)^3(2{\cdot}5-{\cdot}25)-(2{\cdot}5-{\cdot}32)(2{\cdot}6-{\cdot}35)\right.$$
$$\left.\times\{(2{\cdot}6-{\cdot}35)^2+(2{\cdot}6-{\cdot}42)(5{\cdot}2-{\cdot}35-{\cdot}42)\}\right]=13{\cdot}375.$$

By equation (4.),

$$I=13{\cdot}375-3{\cdot}19\times1{\cdot}91^2=1{\cdot}738.$$

By equation (5.),

$$S=Wl\times\frac{1{\cdot}91}{4\times1{\cdot}738}\text{ lbs.}=Wl\times\frac{1{\cdot}91}{15568}\text{ tons.}$$

In experiment 1, $W=3409$, $l=7\times12=84$,

$$\therefore \quad S=\frac{3409\times84\times1{\cdot}91}{15568}=35\text{ tons.}$$

Let $X_1=$ the distance of the neutral axis from the edges AB, and $S_1=$ the force per square inch opposed to extension or compression, as the case may be, at the edge AB, then

$$X_1=2{\cdot}6-1{\cdot}91={\cdot}69,$$

and $$S_1=\frac{X_1}{X}\cdot S=\frac{{\cdot}69\times35}{1{\cdot}91}=12{\cdot}6\text{ tons.}$$

In experiment 2, $W=7735+18=7753$, and $l=27$,

$$\therefore \quad S=\frac{7753\times27\times1{\cdot}91}{15568}=25{\cdot}6\text{ tons,}$$

and $$S_1=\frac{{\cdot}69\times25{\cdot}6}{1{\cdot}91}=9{\cdot}3\text{ tons.}$$

In experiment 3, $W=10759+18=10777$, $l=27$,

$$\therefore \quad S=\frac{10777\times 27\times 1{\cdot}91}{15568}=35 \text{ tons},$$

and $$S_1=12{\cdot}6 \text{ tons}.$$

Taking the data of Table XVIII., experiments 7 and 8,

$$e=1{\cdot}425,\ e_1=2{\cdot}5,\ t={\cdot}2,\ t_1={\cdot}36,\ t_2={\cdot}4,\ t_3={\cdot}12.$$

Hence we find from equation (2.), $A=1{\cdot}762$; from equation (1.), $X=1{\cdot}86$, and $\therefore X_1=2{\cdot}5-1{\cdot}86={\cdot}64$; from equation (3.), $I_1=6{\cdot}943$; and from equations (4.) and (5.), $S=Wl\times{\cdot}00021$ tons.

In experiment 7, $W=3008+11=3019$, $l=48$,

$$\therefore \quad S=3019\times 48\times{\cdot}00021=30{\cdot}4 \text{ tons},$$

and $$S_1=\frac{{\cdot}64\times 30{\cdot}4}{1{\cdot}86}=10{\cdot}4 \text{ tons}.$$

In experiment 8, $W=3142\times 11=3153$, $l=48$,

$$\therefore \quad S=3153\times 48\times{\cdot}00021=31{\cdot}7 \text{ tons},$$

and $$S_1=\frac{{\cdot}64\times 31{\cdot}7}{1{\cdot}86}=10{\cdot}9 \text{ tons}.$$

Observations.—The value of S determined from experiment 1, is the resistance of the material to extension, whereas the value of S determined from experiment 3, is the resistance to compression. Hence it appears, that in beams of this form and *thickness of plates* the resistance to extension is equal to that of compression. The same observation applies to the values of S determined from experiments 7 and 8; and the same law also holds true for experiments 9 and 10.

These calculations further show, that the material in these beams is not properly distributed, for while the thin side of the beam is about to undergo rupture, the broad side has not attained one-half of the tension or compression, as the case may be, which it is capable of sustaining.

It will also be observed, that the resistance of the material at the thin side, as indicated by these calculations, is greater than what it would be under ordinary circumstances, viz. about 25 tons per square inch. This apparent discrepancy may be explained as follows:—as a beam of wrought iron approaches the limit of tension it undergoes an accelerated rate of elongation, even while the cohesion of the material remains unimpaired*. Now this unusual extension of the particles in the lower laminæ (in a beam having a single flanch placed upwards) allows a succession of particles in the higher laminæ to come into full tensile strain, so that the particles at the lower edge of the beam apparently attain a tensile strain greater than they would have under ordinary circumstances. And it may be presumed, that a similar law obtains in reference to the compression of wrought-iron beams. Hence it follows, that all calculations which assume the tensile or compressive forces, in beams of this form, at the edges of the beam equal to what they are under ordinary circumstances, must lead to erroneous results.

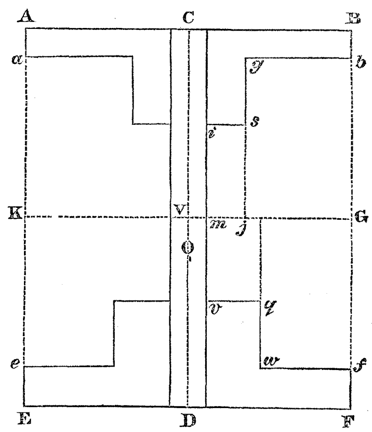
* See remarks on experiment 2, p. 720.

It may be further worthy of remark, that experiments 2 and 3, 8 and 7, show that when the flanches of the beams are placed upwards the deflections are considerably greater than what they are when the flanches are placed downwards; thus in experiments 2 and 3, we have

Weight on the beams. lbs.	Deflections when the flanch is upwards. inch.	Deflections when the flanch is downwards. inch.
6055	·43	·26
6727	·68	·34
7399	·88	·47
and in experiments 8 and 7,		
2470	·66	·59
2739	1·22	·90
3008	2·20	1·35

Beams with a Double Flanch.

Let ABFE be a section of a beam having two flanches ABba and EFfe formed by angle-irons riveted to a vertical plate CD, the material being symmetrically distributed with respect to the vertical line CD. Let O be the neutral axis, and KVG a line passing through the centre V of the vertical line CD parallel to AB or EF. Put A= the area of the section of the material, A_1= area ABFE or 2 area ABGK, $A_2=2$ area $mjsi$, $A_3=2$ area jgbG, $a_2=2$ area $mjqv$, $a_3=2$ area jwfG, D_1=GB=GF, $D_2=sj$, $D_3=b$G, $d_2=jq$, $d_3=f$G, X=OV, I_1= moment of inertia about KG, I= moment of inertia about O, W= the breaking upon the centre of the beam, l= the distance of the supports, S, S_1= the resistance of the material per square inch at the edges EF and AB respectively.



To find the Neutral Axis.

Taking KG as the axis of moments,

$$A\times X=\frac{1}{2}(A_2D_2+A_3D_3-a_2d_2-a_3d_3),$$

$$\therefore \quad X=\frac{A_2D_2+A_3D_3-a_2d_2-a_3d_3}{2A}. \quad (6.)$$

where $$A=A_1-A_2-A_3-a_2-a_3. \quad (7.)$$

To find the Moments of Rupture, &c.

Taking the moments of inertia with respect to the line KG,

$$I_1= \text{moment inertia ABFE}-2\text{ moment inertia space } bgsiqf$$

$$=\frac{1}{3}(A_1D_1^2-A_2D_2^2-A_3D_3^2-a_2d_2^2-a_3d_3^2) \quad (8.),$$

$$I=I_1-AX^2 \quad \ldots \ldots \quad (9.)$$

$$S=\frac{Wl(D_1-X)}{4I} \quad \ldots \ldots \quad (10.)$$

and
$$W=\frac{4SI}{l(D_1-X)}. \quad \ldots \ldots \quad (11.)$$

If
$$a_2=A_2,\ a_3=A_3,$$

then
$$X=0,\ I_1=I,$$

and
$$I=\frac{1}{3}\left\{A_1D_1^2-2A_2D_2^2-2A_3D_3^2\right\},$$

$$\therefore\ S=\frac{WlD_1}{4I}$$

$$=\frac{3WlD_1}{4\{A_1D_1^2-2A_2D_2^2-2A_3D_3^2\}} \quad \ldots \ldots \quad (12.)$$

and
$$W=\frac{4S(A_1D_1^2-2A_2D_2^2-2A_3D_3^2)}{3lD_1}, \quad \ldots \ldots \quad (13.)$$

which expresses the breaking weight when S is given.

Let D'_1, D'_2, ..., A', A_1, ... &c. be the corresponding dimensions of a beam in all respects similar, and let r be the ratio of the linear dimensions, then

$$D'_1=rD_1,\ \&c.,\quad A'=r^2A_1,\ \&c.,\quad A'_2D'_2=r^3A_2D_2,\ \&c.,\quad A'_1D'^2_1=r^4A_1D_1^2,\ \&c.$$

By equation (6.),

$$X'=\frac{A'_2D'_2+A'_3D'_3-a'_2d'_2-a'_3d'_3}{2A'}$$

$$=\frac{r^3A_2D_2+r^3A_3D_3-r^3a_2d_2-r^3a_3d_3}{2r^2A}$$

$$=r\times\frac{A_2D_2-A_3D_3-a_2d_2-a_3d_3}{2A}$$

$$=r\times X.$$

By equation (8.),

$$I'_1=\frac{1}{3}\left\{A'_1D_1^2-A'_2D'^2_2-A'_3D'^2_3-a'_2d'^2_2-a'_3d'^2_3\right\}$$

$$=r^4\times\frac{1}{3}\left\{A_1D_1^2-A_2D_2^2-A_3D_3^2-a_2d_2^2-a_3d_3^2\right\}$$

$$=r^4\times I_1.$$

By equation (11.),

$$W'=\frac{4SI'}{l'(D'_1-X')}$$

$$=\frac{4S\times r^4I}{rl(rD_1-rX)}$$

$$=r^2\times\frac{4SI}{l(D_1-X)}$$

$$=r^2\times W \quad \ldots \ldots \quad (14.)$$

That is, THE BREAKING WEIGHTS IN SIMILAR BEAMS ARE TO EACH OTHER AS THE SQUARES OF THEIR LIKE LINEAR DIMENSIONS.

The method of demonstration here used in establishing this important theorem may be applied to any other form of beam.

When the sections of the beams are similar, but the distance between the supports any quantity l_1, then we have

$$W'=\frac{l'}{l_1}.r^2W. \qquad (15.)$$

Suppose W in equation (11.) to be determined by experiment, then we are at liberty to assume

$$W=\frac{AdC}{l},$$

where d is the depth of the beam, and C a constant determined by the assumed relation.

From equation (14.),

$$\begin{aligned}W'&=r^2W\\&=r^2.\frac{AdC}{l}\\&=\frac{r^2A.rd.C}{rl}\\&=\frac{A'd'C}{l'}. \qquad (16.)\end{aligned}$$

That is, THE BREAKING WEIGHTS IN BEAMS ARE FOUND BY MULTIPLYING TOGETHER THE AREA OF THE SECTION, THE DEPTH, AND A CONSTANT DETERMINED FROM EXPERIMENT ON BEAMS OF THE PARTICULAR FORM, AND DIVIDING THIS PRODUCT BY THE DISTANCE BETWEEN THE SUPPORTS.

The value of l' in this formula is not restricted to the condition of similarity.

In experiment 12,

$D_1=3{\cdot}5, D_2=1{\cdot}375, D_3=3{\cdot}22, d_2=1{\cdot}375, d_3=3{\cdot}2, W=24380+80=24460, l=84,$

$A_1=4{\cdot}5\times7=31{\cdot}5,\ A_2=1{\cdot}375\times{\cdot}28\times2={\cdot}7,\ A_3=3{\cdot}22\times1{\cdot}845\times2=11{\cdot}8818,$

$a_2=1{\cdot}375\times{\cdot}3\times2={\cdot}75,\ a_3=3{\cdot}2\times1{\cdot}825\times2=11{\cdot}68,$

$A=A_1-A_2-A_3-a_2-a_3=32{\cdot}5-25{\cdot}01=6{\cdot}48,$

$\therefore$ by equation (6.), $X={\cdot}0611$.

By equation (8.), $I_1=46{\cdot}782$.

By equation (9.), $I=46{\cdot}782-6{\cdot}48\times{\cdot}0611^2=46{\cdot}758$.

By equation (10.),

$$S=\frac{24460\times84(3{\cdot}5-{\cdot}0611)}{4\times46{\cdot}758\times2240}=17 \text{ tons nearly},$$

and $S_1=17\frac{1}{2}$ tons nearly.

In experiment 13, $W=21715+80=21800$ nearly,

and

$$S_1=\frac{21800\times84(3{\cdot}5+{\cdot}0611)}{4\times46{\cdot}7854\times2240}=15{\cdot}5 \text{ tons},$$

$$S=\frac{21800\times84(3{\cdot}5-{\cdot}0611)}{4\times46{\cdot}7854\times2240}=15 \text{ tons}.$$

The values of S and S_1, as determined by these calculations, being less for the beam in experiment 13 than they are for the beam in experiment 12, it follows that the latter has a better distribution of the material than the former. And at the same time the difference of the value of these constants is so small as to lead us to infer that the form of the beam in experiment 12 approaches to that of maximum strength with a given quantity of material. The sectional areas of the top and bottom flanches are to each other as 28 : 30 or 14 : 15, which is very nearly a ratio of equality.

APPENDIX.

Experiments by Thomas Loyd, Esq., Inspector of Machinery, to ascertain the effect of a tensile strain upon bars of wrought iron under varied conditions. Twenty pieces of $1\frac{3}{8}$ S C bar iron, each 10 feet long, were cut out of the middle of twenty rods of iron. These 10-feet lengths were cut into two parts of 5 feet each, and marked with the same letter. A, B, C, &c. were first broken so as to get the average breaking strain. A^2_2, B^2_2, C^2_2 were subjected to the constant action of three-fourths of the breaking weight for five minutes. The load was then taken off, and they were afterwards broken. It will be seen that the breaking strain was about the same as before, thus proving that the previous strain had not weakened them.

Experiment 1.

First.				Second.			
Mark on the bars.	Dimensions of the bars.	Breaking weight in tons.	Ultimate elongation of bar in inches.	Mark on the bars.	Dimensions of the bars.	Breaking weight in tons.	Ultimate elongation of bars in inches with 25 tons.
A.	1·37	33·75	9·12	A 2.	......	33·75	1·56
B.	1·37	30·00	9·12	B 2.	......	33·00	1·61
C.	1·37	33·25	9·75	C 2.	......	33·25	1·56
D.	1·37	32·75	9·22	D 2.	......	32·25	1·75
E.	1·37	32·50	9·22	E 2.	......	32·50	1·75
F.	1·37	33·25	10·50	F 2.	......	33·00	1·56
G.	1·37	32·75	8·50	G 2.	......	33·00	1·61
H.	1·37	33·25	10·61	H 2.	......	33·50	1·50
I.	1·37	33·50	8·37	I 2.	......	32·75	1·67
J.	1·37	33·50	9·22	J 2.	......	33·25	1·67
K.	1·37	32·25	8·00	K 2.	......	32·50	1·86
L.	1·37	32·25	7·50	L 2.	......	31·50	2·00
M.	1·37	30·25	9·12	M 2.	......	32·75	Broke mark 1·75 in s. c.
N.	1·37	34·25	9·22	N 2.	......	34·00	1·12
O.	1·37	31·75	7·61	O 2.	......	32·50	1·75
P.	1·37	29·75	10·00	P 2.	......	31·00	1·75
Q.	1·37	33·50	9·22	Q 2.	......	33·75	1·50
R.	1·37	33·75	9·75	R 2.	......	33·75	1·56
S.	1·37	33·00	9·12	S 2.	......	33·25	1·12
T.	1·37	32·25	8·75	T 2.	......	31·00	2·18
Mean ...	......	32·87	9·09		......	32·81	1·64

In the first columns of the experiments it will be observed that the force required to break the bars was 32·37 tons, with a mean stretch of 9 inches upon twenty bars. In the second column the mean of the elongations, with a strain of 25 tons, was only 1·6 inch, whereas the ultimate breaking strain was 32·8 tons, evidently showing an increase instead of a diminution of strength from the previous strain of 25 tons, to which the bars had been respectively subjected.

Experiments made in the testing-machine of Woolwich Dockyard to ascertain the effect upon iron-bolt staves or iron bars to a tensile strain. The following results show the strains required for each of four successive breakages of the same pieces of iron as in the first experiment, $1\frac{3}{8}$ths of an inch diameter S C.

Experiment 2.

Distinguishing mark.	First breakage.		Second breakage.		Third breakage.		Fourth breakage.		Redueed from 1·37 to
	Tons.	Stretch in 54 inches.	Tons.	Stretch in 36 inches.	Tons.	Stretch in 24 inches.	Tons.	Stretch in 15 inches.	
		in.		in.		in.		in.	in.
A.	33·75	9·125	35·5	2·00					
C.	33·75	9·250	35·25	·25	37·00	1·00	38·75	......	1·25
E.	32·5	9·250	34·75	1·25					
F.	33·25	10·500	35·50	1·12	37·25	·62	·40	......	1·18
G.	32·75	8·500	35·00	1·25	37·5	......	·41	......	1·25
H.	33·75	10·625	36·25	1·87					
I.	33·50	8·375	34·50	·62	36·5	1·50			
J.	33·50	9·250	36·00	·25	36·75	1·120	41·75	......	1·25
L.	32·25	Defective	36·50	1·5	37·75	......	41·00	·31	1·25
M.	30·25	Defective	36·50	·62	37·75	·06	38·50	·06	1·25
Mean	32·92	......	35·57	......	37·21	......	40·16	......	1·24
Mean per square inch...........	23·94	......	25·86	......	27·06	......	29·20	......	·90

The results of the above experiments are highly interesting, as they not only confirm those previously made, but they indicate a progressive increase of strength, notwithstanding the reduced sectional area of the bars. These interesting facts are of considerable value, as they show that a severe tensile strain is not injurious to the bearing powers of wrought iron even when repeated to the extent of four times. In practice it may not be prudent to test bars and chains to their utmost limit of resistance; it is however satisfactory to know that in cases of emergency those limits may be approached without incurring serious risk of injury to the ultimate strength of the material.

It is further important to observe, that the elongations are not in proportion to the forces of extension; thus in the bar F, experiment 2, the elongation of a bar 54 inches long with 33·25 tons, is 10·5 inches, giving an elongation per unit of weight and length$=\frac{10\cdot5}{33\cdot25\times54}=\cdot0058$; whereas an additional weight of 2·25 tons produces an

elongation of 1·25 inch in 36 inches length of bar, giving an elongation per unit of weight and length$=\frac{1·25}{2·25\times 36}=·0154$; that is, the elongation in this latter case is about three times that in the former.

Experiments made to ascertain whether a shorter bar of iron is stronger than a longer one of the same kind and size, $1\frac{3}{8}$ths of an inch diameter, SC.

Experiment 3.

Length between the nippers 10 feet.						
Distinguishing mark.	Stretch in 10 feet.	Breaking strain.	Mean.	Reduced at fracture.	To elsewhere.	Remarks.
	in.	tons.	tons.	in.	in.	
1.	26·00	33·00		1	1·25	
2.	26·75	31·75		......	1·18	
3.	26·25	32·25	32·21	......	1·25	Mean of elongation 26 inches.
4.	23·00	32·00		......	......	
5.	27·50	32·25		B.	B.	
6.	26·75	32·00		1·06	......	

Experiment 4.

Length between the nippers 42 inches.						
Distinguishing mark.	Stretch in 42 inches.	Breaking strain.	Mean.	Reduced at fracture.	To elsewhere.	Remarks.
	in.	tons.	tons.	in.	in.	
B.	9·50	32·50		1·06	1·25	
B.	9·37	33·00		B.	....	
B.	10·25	31·75	32·125	1	B.	Mean of elongation 9·8 inches.
B.	10·37	31·50		......	B.	
B.	8·62	32·00		1·06	F.	
B.	8·87	32·00		F.	F.	

Experiment 5.

Length between the nippers 36 inches.						
Distinguishing mark.	Stretch in 36 inches.	Breaking strain.	Mean.	Reduced at fracture.	To elsewhere.	Remarks.
	in.	tons.	tons.	in.	in.	
A.	8·50	32·25		1·06	1·25	
A.	8·75	32·25		1	B.	
A.	9·00	31·25	32·25	F.	B.	Mean of elongation 8·8 inches.
A.	9·12	31·50		......	......	
A.	9·37	33·50		B.	B.	
A.	8·87	33·25		B.	B.	

Experiment 6.

Length between the nippers 24 inches.						
Distinguishing mark.	Stretch in 2 feet.	Breaking strain.	Mean.	Reduced at fracture.	To elsewhere.	Remarks.
	in.	tons.	tons.	in.	in.	
C 1.	6·00	31·75	32·00	1	1·25	Mean of elongation 6·2 inches.
C 2.	6·62	31·50		1·06 B.	F.	
C 3.	6·12	32·50		1		
C 4.	6·12	31·75		1		
C.	6·00	32·25		1		
C.	6·37	32·25		......	B.	

Experiment 7.

Length between the nippers 10 inches.						
Distinguishing mark.	Stretch in 10 inches.	Breaking strain.	Mean.	Reduced at fracture.	To elsewhere.	Remarks.
	in.	tons.	tons.	in.	in.	
A.	4·00	32·25	32·29	1·06	1·25	Mean of elongation 4·2 inches.
A.	3·87	32·50				
A.	4·62	30·50		B.	B.	
A.	4·75	31·50		1	1·18	
A.	4·00	33·25		......	1·25	
A.	4·12	33·75				

Abstract of the foregoing.

Length between the nippers.	Breaking strain in tons.	Mean elongation in inches.
in.		
120	32·21	26
42	32·125	9·8
36	32·35	8·8
24	32·00	6·2
10	32·29	4·2

As these experiments were made upon the same description of iron, it may be fairly inferred that the length of a bar does not in any way affect its strength.

Reduction of the preceding Table.

Length of bar.	Elongation.	Elongation per unit of length.
in.		
120	26	·216
42	9·8	·233
36	8·8	·244
24	6·2	·258
10	4·2	·420

Here it appears that the rate of elongation of bars of wrought iron increases with the decrease of their length; thus while a bar of 120 inches has an elongation of ·216 inch per unit of its length, a bar of 10 inches has an elongation of ·42 inch per unit of its length, or nearly double what it is in the former case. The relation between the length of and its maximum elongation per unit, may be approximately expressed by the following formula, viz.—

$$l = \cdot 18 + \frac{2\cdot 5}{L},$$

where L represents the length of the bar, and l the elongation per unit of length of the bar.

These results are of some value, as they exhibit the ductility of wrought iron at a low temperature, and also the greatly increased strength which it exhibits with a reduced section under severe strain.

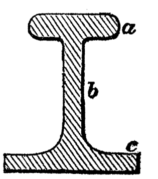
On some future occasion we may refer to this subject in order to show the bearing powers of wrought iron when compared with its elongated transverse section when reduced by forces sufficient to ensure fracture.

The following experiments were made to determine the transverse strength of beams, recommended by Mr. Kennedy of Liverpool, for supporting the decks of iron ships.

Experiment 8.—October 10, 1845.

On a malleable iron beam, of the annexed sectional form, 11 feet 7 inches long, and 11 feet between the supports.

Dimensions at $a = 1\cdot 000$ in. $\times 2\frac{1}{2}$ in.
Dimensions at $b = \cdot 325$ in. $\times 7$ in.
Dimensions at $c = \cdot 380$ in. $\times 4$ in.
Weight of beam=227 lbs.
Weight of shackle=885 lbs.



Weight in lbs.	Deflection in inches.	Deflection load removed.	Remarks.
885	·04		
2,581	·12		
4,317	·20		
6,050	·26		
7,743	·35		
9,493	·46		
11,253	·60	·09	
12,955	......	......	With this weight the beam became distorted, and continuing the weight for some time, the deflection kept increasing until it bent laterally so as to be no longer able to sustain the load.
Ultimate deflection=·69.			

Experiment 9.—October 10, 1845.

On a malleable iron beam, of the annexed sectional form (see fig. 66), 10 feet 8 inches long, and 10 feet between the supports.

Dimensions at a=1·000 in.×$2\frac{3}{7}$ in.
Dimensions at b= ·350 in.×8 in.
Dimensions at c= ·440 in.×4·30 in.
Weight of beam=247 lbs.
Weight of shackle=885 lbs.

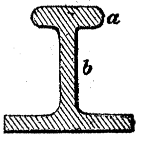
Weight in lbs.	Deflection in inches.	Deflection load removed.	Remarks.
885			
2,631	·04		
4,358	·12		
6,098	·15		
7,827	·19		
9,585	·21		
11,278	·26		
12,980	·30	·03	
14,693	·35	·03	
16,373	·45	·09	
18,115	·68	·26	
18,962	......	......	With this weight the beam was distorted and the experiment discontinued.
Ultimate deflection=·71.			

In both these experiments the beams yielded to lateral deflection, showing certain defects of form arising from want of lateral strength and breadth in the top and bottom flanges.

Experiment 10.—October 10, 1845.

Malleable iron beam of the same form as the last, 10 feet 7 inches long and 10 feet between the supports.

Thickness, $a = 1{\cdot}000$ in. $\times\, 2{\cdot}75$ in.
Thickness, $b = {\cdot}380$ in. $\times\, 8$ in.
Thickness, $c = {\cdot}420$ in. $\times\, 4{\cdot}30$ in.
Weight of beam $= 276$ lbs.



Weight in lbs.	Deflection in inches.	Deflection load removed.	Remarks.
885	·020		
2,606	·050		
4,364	·090		
6,105	·100		
7,835	·140		
9,559	·165	·03	
11,257	·195	·03	
12,999	·220	·04	
14,728	·250		
16,407	·250		
18,108	·290		
19,839	·370		
21,553	·475	......	With 21,553 lbs. the deflection increased in four minutes ·025; in the next four minutes ·10; and in four minutes more it had sunk to ·34.
22,387	·590		
23,046	......	......	Bent laterally upwards of 2·65 inches, when the experiment was discontinued.
Ultimate deflection = ·6.			

In these experiments it will be necessary to remark, that they were made with the narrow flange uppermost; a position rather favourable to the strength than otherwise, on account of the increased area of the top flange, which is equal to 2·75 inches; and the bottom flange is only 1·8 inch, a circumstance (deduced from subsequent experiments) favourable to the resisting powers of a wrought-iron beam.

Manchester, April 10, 1850.